

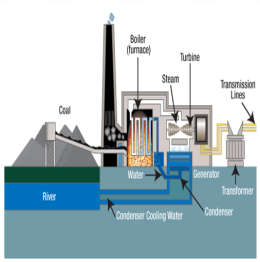
Fundamentals of power plant

- *Power plant is assembly of systems or subsystems to generate electricity, i.e, to produce power with economy and requirements.*
- *So the power produced must be*
 1. *economically useful.*
 2. *Environmental friendly to society*
- Therefore, power plant can be defined as :
- “a machine or assembly of equipment that generate and deliver a flow of mechanical or electrical energy.
- or, power plant may also be defined as:
- The engineering and technology required for the production of central station electric power

Classification of power plant

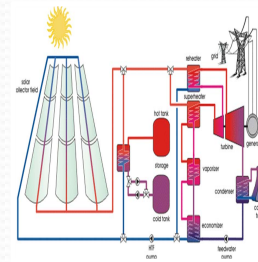
- Methods of general classification of electricity generation power plant are as follows :
 1. Status
 2. Fuel type
 3. Capacity
 4. Operation
 5. Prime mover

1 - status



conventional

- Steam turbine PP
- Steam engine PP
- Diesel PP
- Gas turbine PP
- Hydro-electric PP
- Nuclear PP



Non-conventional

- Wind energy PP
- Geothermal energy
- Ocean thermal energy
- Wave & tidal wave
- Solar energy
- Biogas & biomass energy

2 – fuel type

Heat engine fuel

- Where mechanical power is produced by heat engine, which transfer thermal energy from combustion of fuel to rotational mechanical energy

Nuclear PP

- Nuclear reactors heat is used to generate steam and thus operates steam turbine

Fossil fuel

- Where natural gas fired plant may be used in steam turbine or gas turbine

Geothermal power

- Steam is extracted from hot underground source.

Renewable energy

- Waste, biomass, wind power, solar energy .. etc

3 - capacity

Power plant can be classified according to it's capacity :

- I - Small power plant : producing less than (5 MW)	- II - Medium capacity plant : production capacity lies in the range of (5 – 100) MW	- III - High capacity plant : Have production range of (101 – 1000) MW	- IV - Super capacity plant : Exceeds (1000) MW power production level
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4 – operation

see hand-outs

1 – base plant

- Loaded as heavily as possible, where it's load never falls below demand

2 – peak load

- Used in a small fraction of time

3 – intermediate load

- These small and old existing plant

5 – prime mover

1 – steam turbine

2 – gas turbine

3 – water turbine

4 – wind turbine

5 – combined cycle

6 – heat engine

7 – other sources as wave, sun light,
...etc

1.00 - Power plant fundamentals

1.02 - Power plant
Types & description

Types of power plants

As previously mentioned, power plants can be classified in different ways.

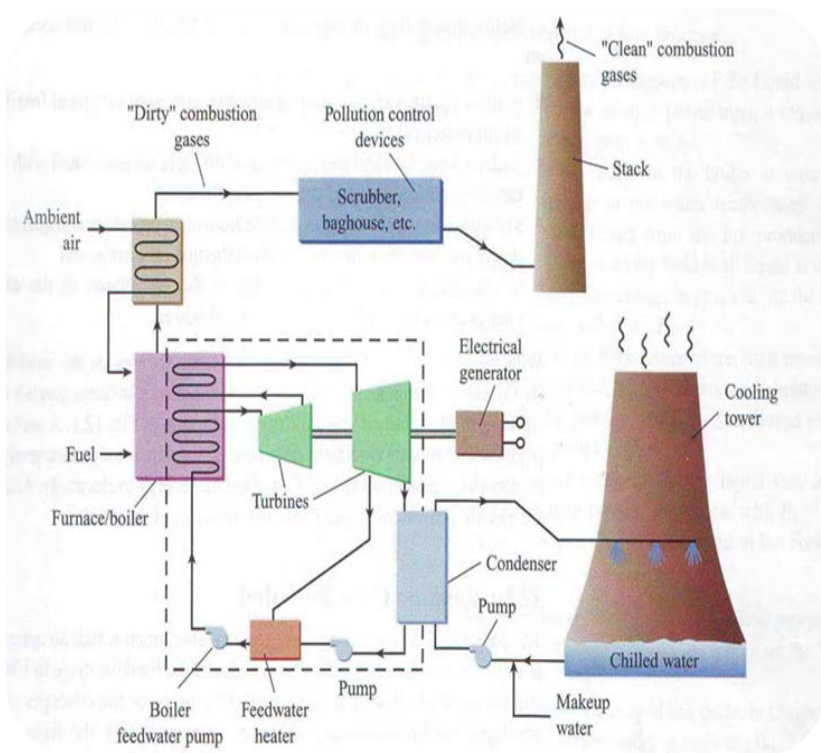
However, fuel types and prime mover used is of major importance, and so we can select the types of power plants of our concern accordingly

The following power plants are to be studied in details during this course.

- 1 – steam PP
- 2 – gas turbine PP
- 3 – combined cycle PP
- 4 – hydro-electric PP
- 5 – nuclear PP
- 6 – wind turbine PP

1 – steam power plant

Steam power plants use fuels such as petroleum, coal, or biomass are burned to heat water to create steam, the pressure of the steam spins a turbine turning the copper wire inside the generator.



1 – steam generator

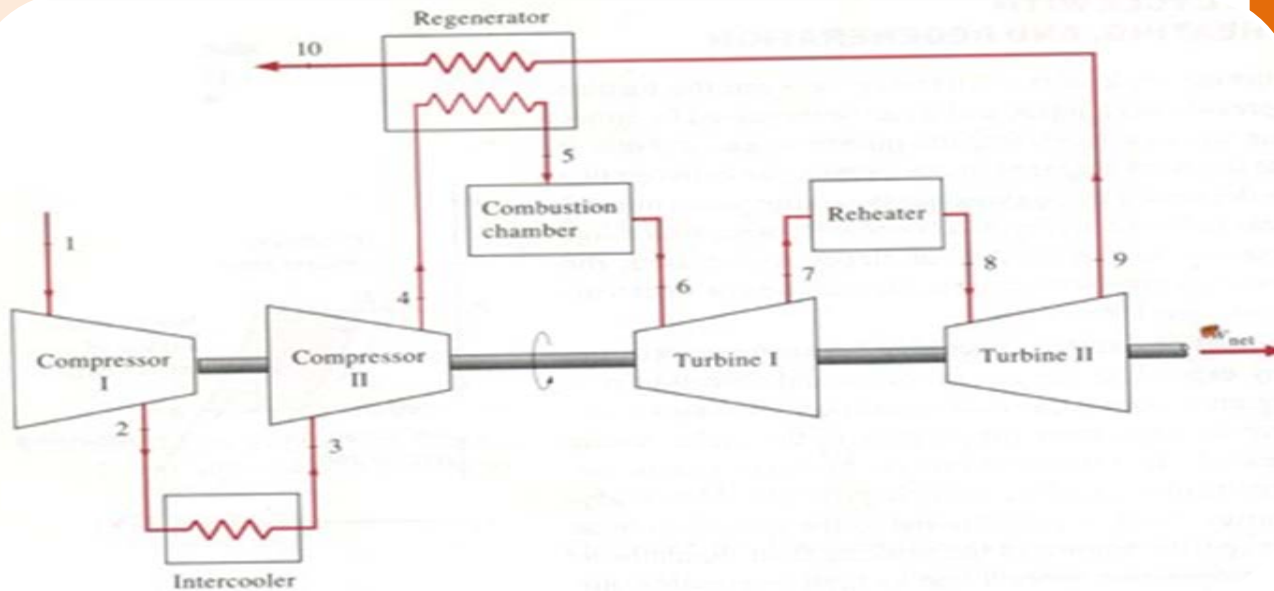
2 – turbine

3 – condenser

4 – pressure pump

5 -Plus other parts such as water heaters, cooling water system regenerators, re-heaters, water treatment system ... etc

2 – gas turbine plant



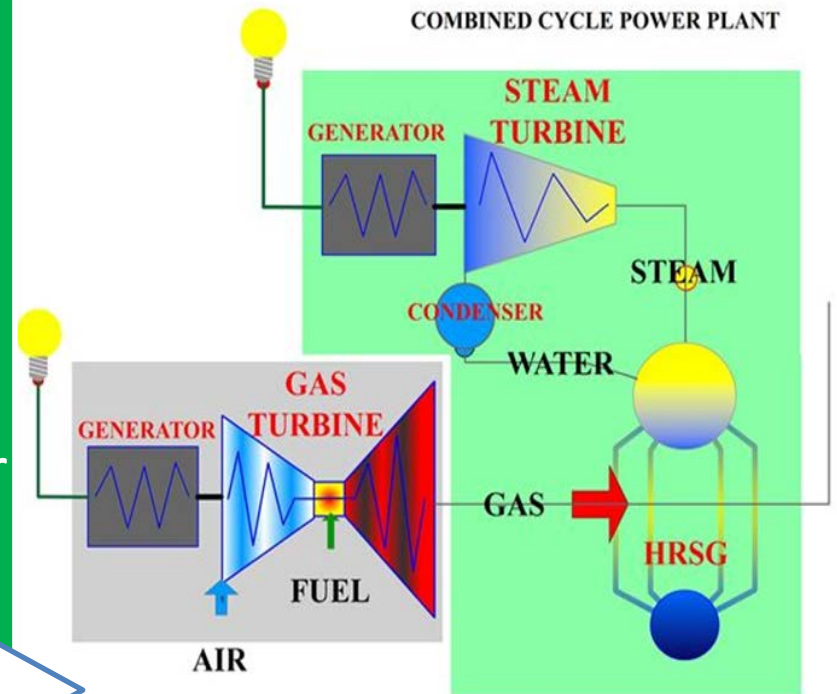
Gas turbine plant major component are :

Gas power plants uses fuels that are burned to create hot gases to spin the turbine.

- 1 – compressor
- 2 – combustor
- 3 – gas turbine
- 4 - Plus others as inter-cooler, after-cooler, regenerator, re-heater, cooling water system

3 – combined cycle plant

The combined-cycle unit combines the Rankine (steam turbine) and Brayton (gas turbine) thermodynamic cycles by using heat recovery boilers to capture the energy in the gas turbine exhaust gases for steam production to supply a steam turbine as shown in the figure .

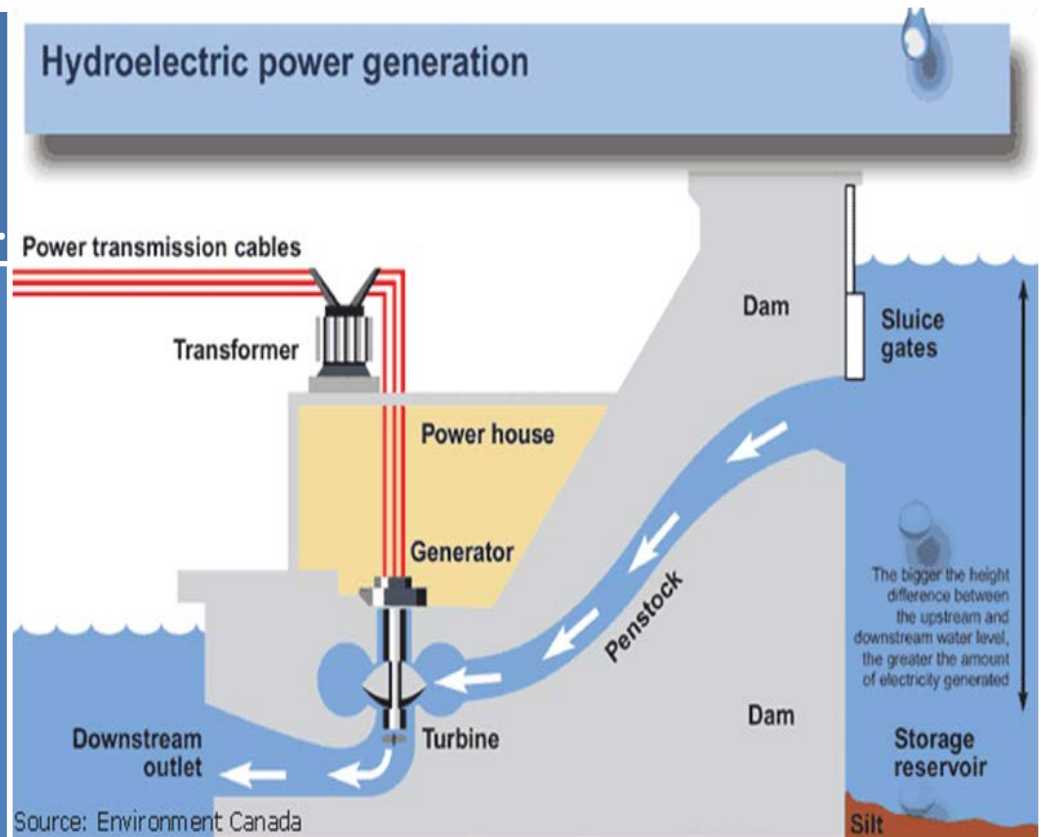


4 – hydro-electric plant

Hydroelectric plant use falling (or flowing) water to spin the turbine blades.

Water flowing in high altitude rivers is stored in a man-made reservoir as shown in the figure. The kinetic energy of the flowing water is transformed into potential energy as the water level rises. This water is carried through pipes to the turbine situated at the bottom of the dam.

A jet of moving water rotates the water turbine rapidly which in turn rotates the shaft which is attached to its centre.

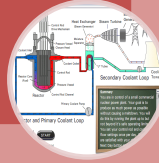


5 – nuclear power plant

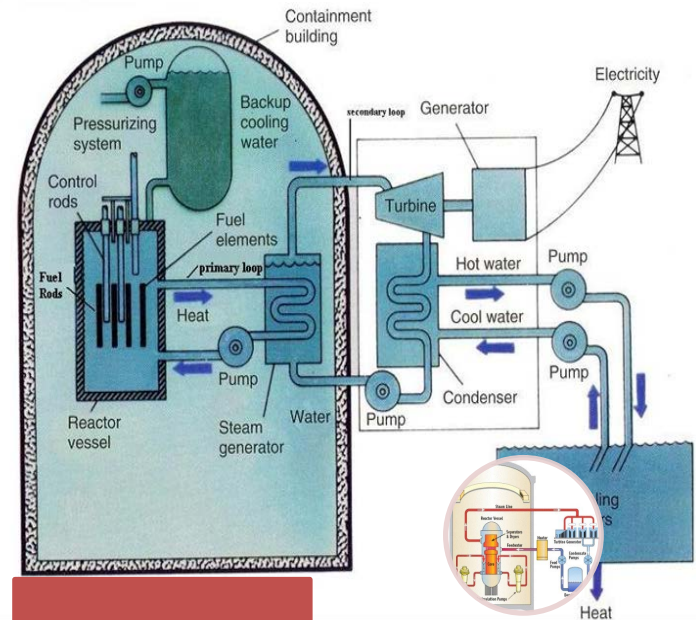
- Nuclear power plants use nuclear fission to turn water into steam. This drives the steam turbine, which spins a generator to produce power.



- Grams of highly enriched uranium can power a nuclear submarine or nuclear aircraft carrier is equal to something on the order of a million gallons of gasoline.



Schematic of a Nuclear Power Plant

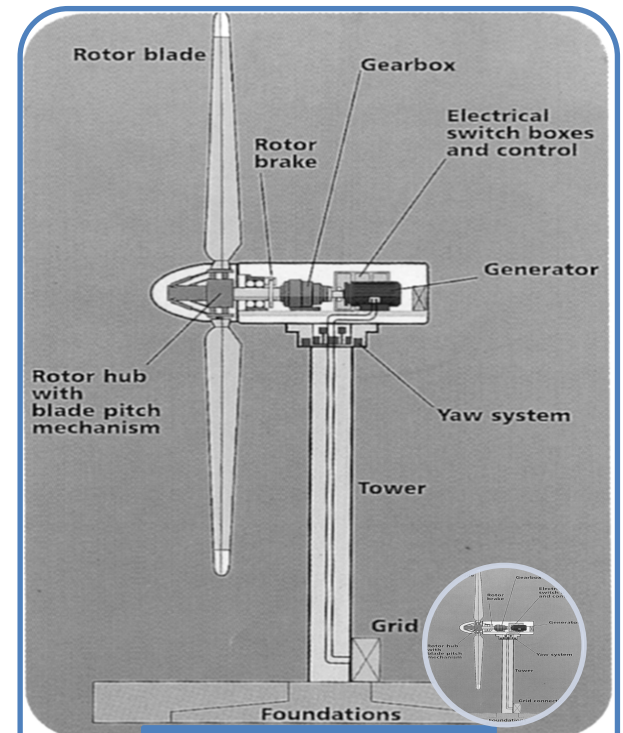


6 – wind turbine plant



Wind farm

- **Wind power plants** use the wind to push against the turbine blades, spinning the copper wires inside the generator to create an electric current.



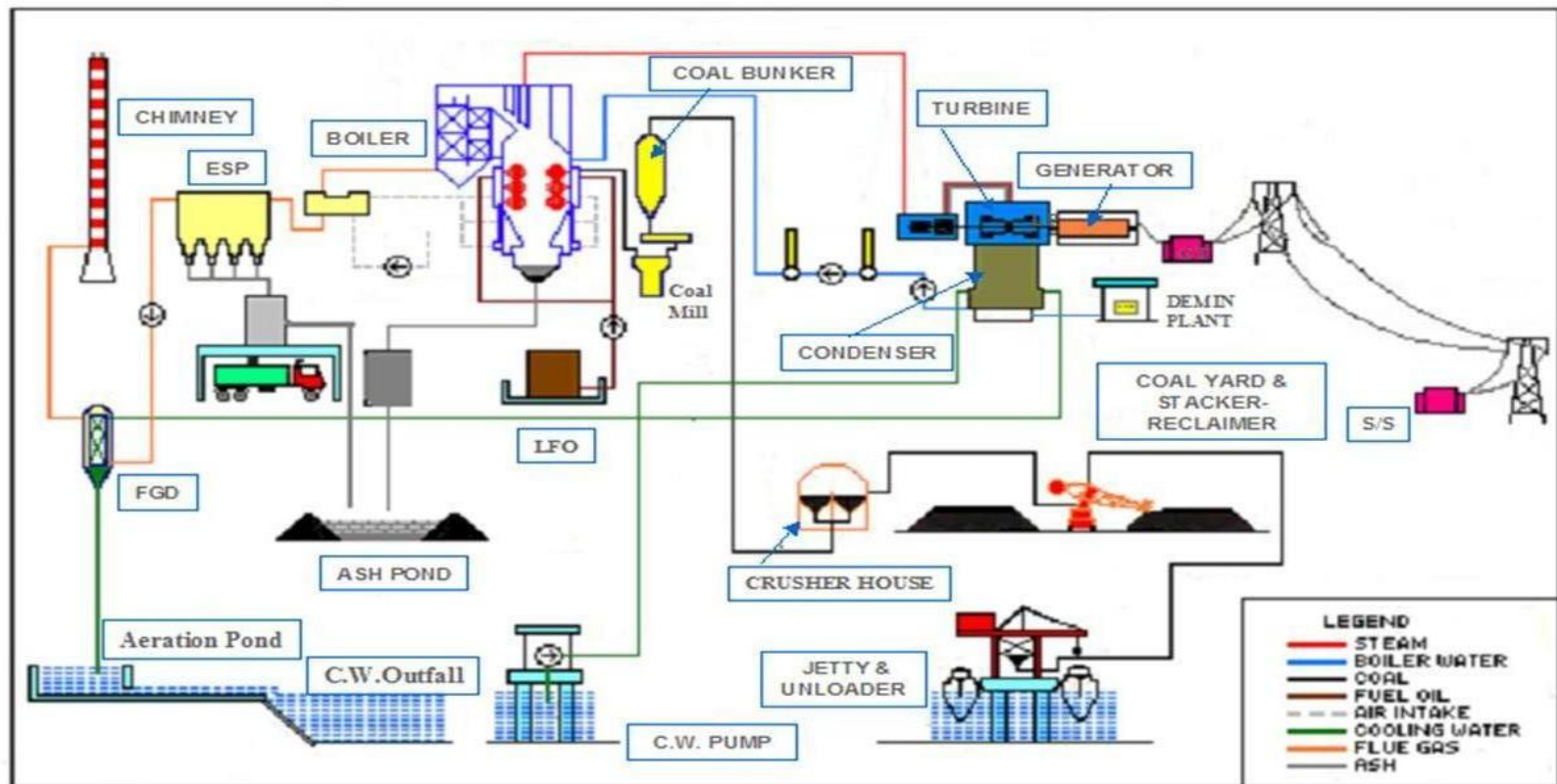
Wind turbine structure

Chapter one

Power plant fundamentals

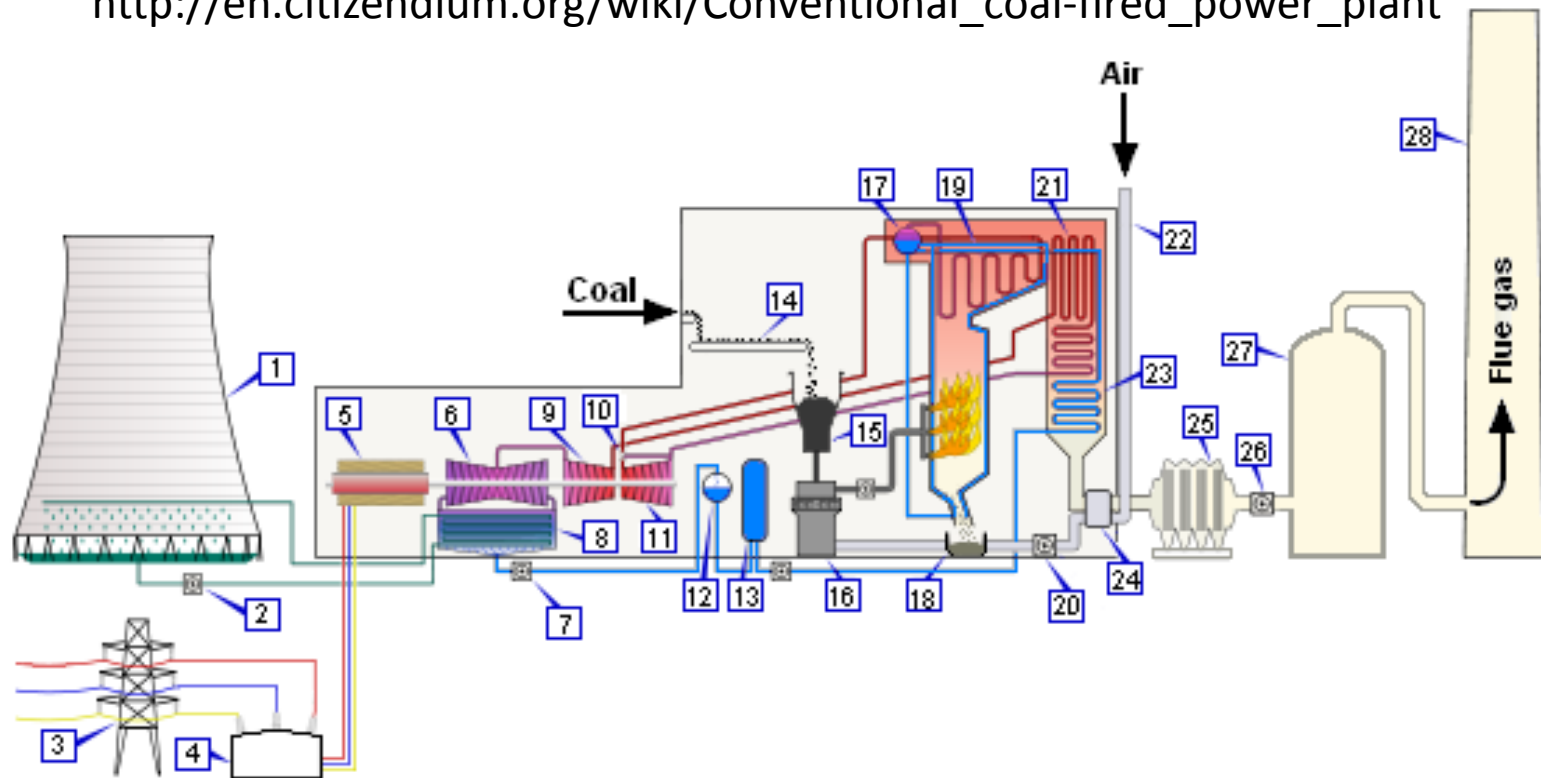
1.03 – steam power plant
‘parts & components’

COAL-FIRED POWER PLANT PROCESS



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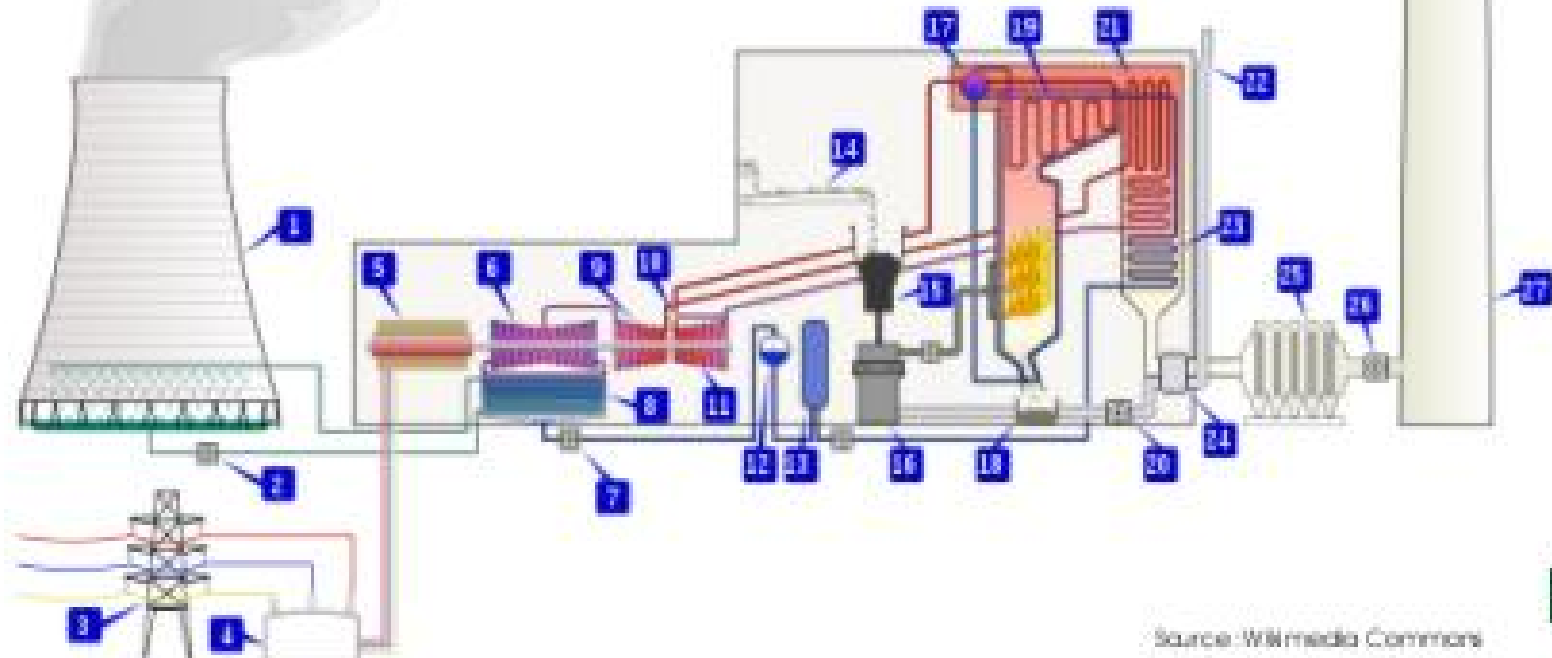
Simplified coal-fired power plant

- | | | |
|--------------------------------------|---------------------------------|--------------------------------|
| 1. Cooling tower | 11. High pressure steam turbine | 20. Fan |
| 2. Cooling water pump | 12. Deaerator | 21. Reheater |
| 3. Three-phase transmission line | 13. Feedwater heater | 22. Combustion air intake |
| 4. Step-up transformer | 14. Coal conveyor | 23. Economiser |
| 5. Electrical generator | 15. Coal hopper | 24. Air preheater |
| 6. Low pressure steam turbines | 16. Coal pulverizer | 25. Electrostatic precipitator |
| 7. Boiler feedwater pump | 17. Steam drum | 26. Fan |
| 8. Surface condenser | 18. Bottom ash hopper | 27. Flue gas scrubber |
| 9. Intermediate press. steam turbine | 19. Superheater | 28. Flue gas stack |
| 10. Steam control valve | | |

1. Cooling tower
2. Cooling water pump
3. Transmission line (3-phase)
4. Unit transformer (3-phase)
5. Electric generator (3-phase)
6. Low pressure turbine
7. Condensate extraction pump
8. Condensor
9. Intermediate pressure turbine

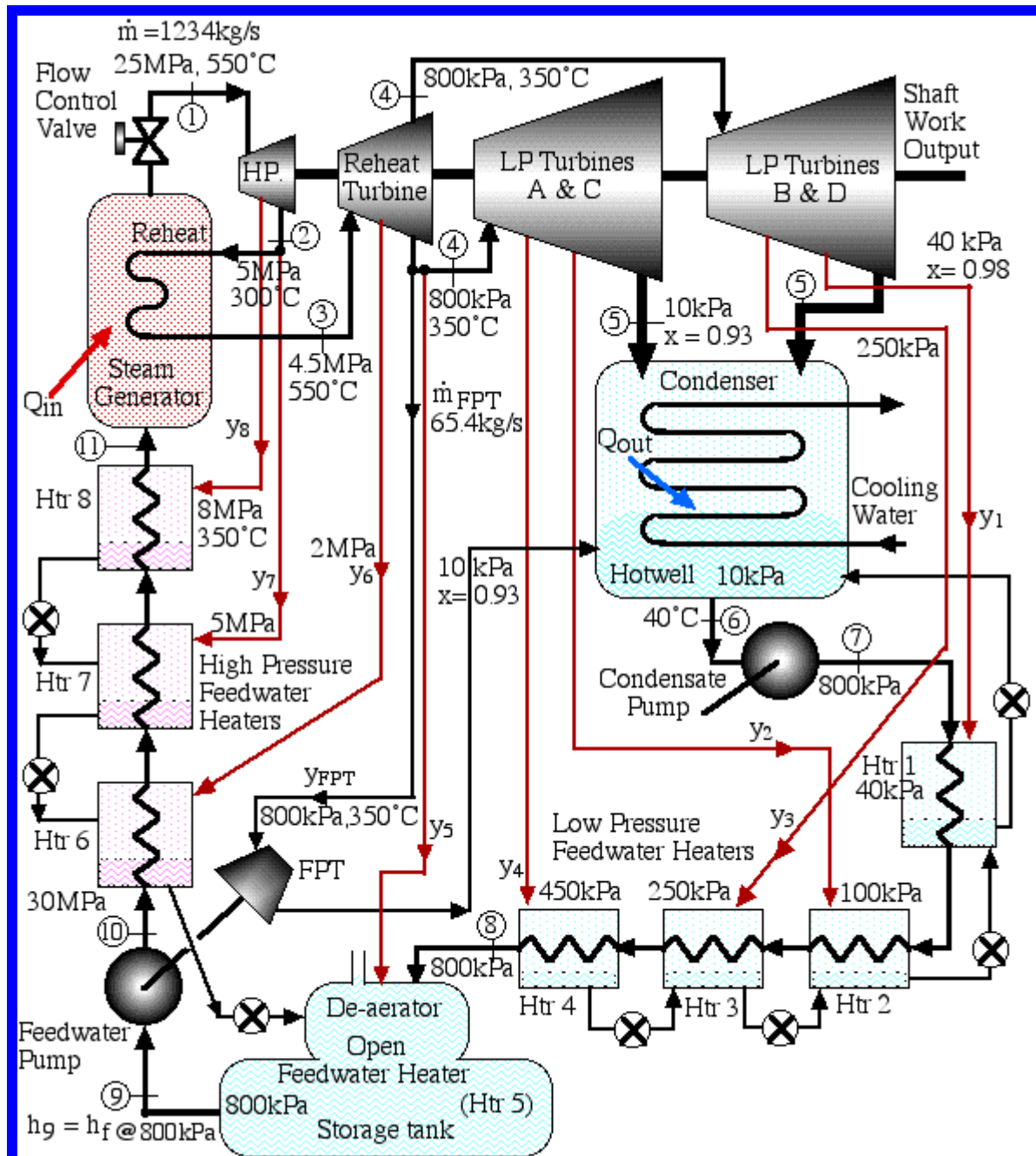
10. Steam governor valve
11. High pressure turbine
12. Deaerator
13. Feed heater
14. Coal conveyor
15. Coal hopper
16. Pulverised fuel mill
17. Boiler drum
18. Ash hopper

19. Superheater
20. Forced draught fan
21. Reheater
22. Air intake
23. Economiser
24. Air preheater
25. Precipitator
26. Induced draught fan
27. Chimney Stack



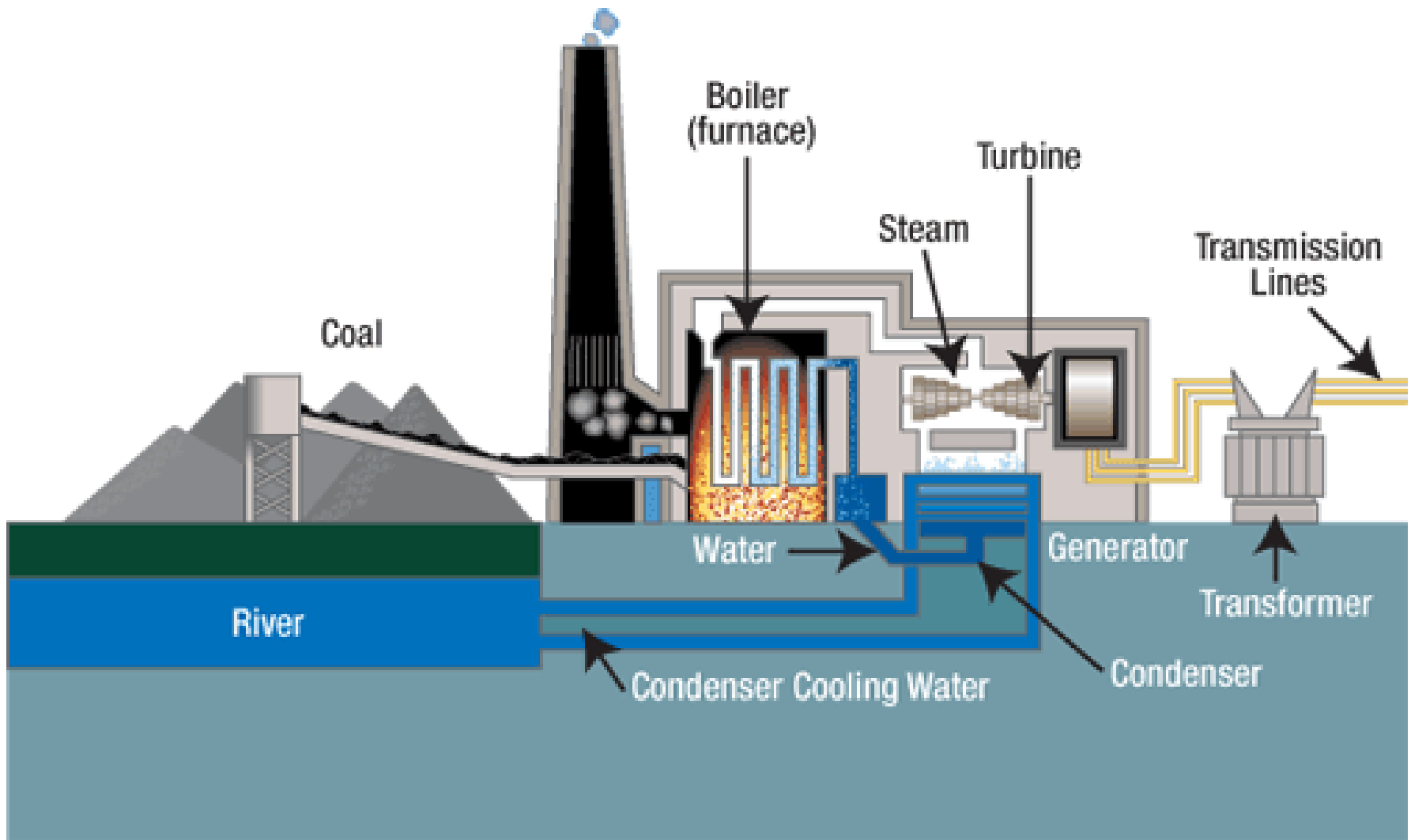
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The plant

- Though the main process in steam power station is the conversion of heat energy into electrical energy, it comprises of many steps for its proper working and good efficiency. The whole arrangement of a steam power station could be divided into following steps. The whole arrangement is shown in a schematic figure given below.
- Coal and ash handling arrangement
- Steam generating plant
- Steam turbine
- Alternator
- Feed water
- Cooling arrangement



1. Coal and ash handling

- The coal is transported from different places to the station by means of rails or road and is stored in a coal storage plant. It is to use as a preserve at the time of scarcity. From coal storage plant it is transferred to coal handling plant for pulverization. **Pulverization is the process by which large lumps of coal are broke to small pieces.**
- **Why Pulverization is done?**
- Pulverization is done to increase the surface area of coal and thereby helping the easy combustion of coal with small intake of air. The pulverized coal is fed to the boiler by means of conveyor belt. The coal is burnt in the boiler and the ash so produced by burning is removed to the ash handling system and finally to the ash storage area for its disposal. This process is necessary since ash in the boiler furnace does not promote proper combustion.

Pulverizer

is a mechanical device for the grinding of many different types of materials. For example, they are used to pulverize coal for combustion in the steam-generating furnaces of fossil fuel power plants.

The coal is put in the boiler after pulverization. For this , pulverizer is used. A pulverizer is a device for grinding coal for combustion in a furnace in a power plant.

Types of Pulverizers

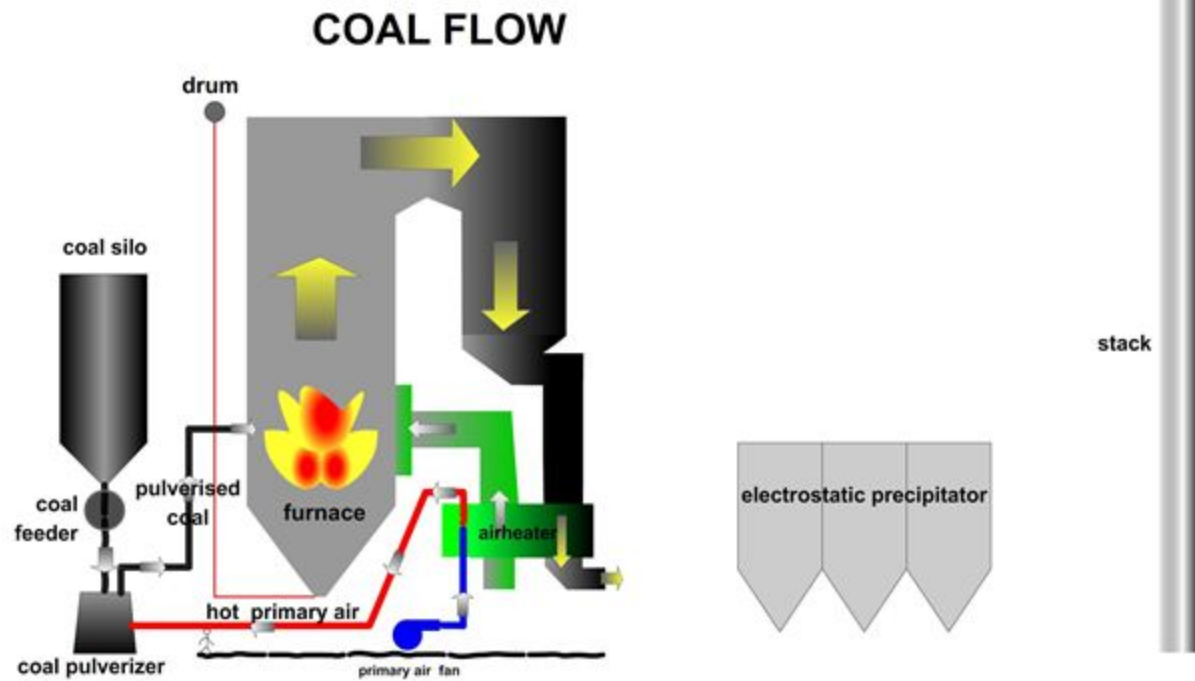
I - Ball and Tube Mill

Ball mill is a pulverizer that consists of a horizontal rotating cylinder, up to three diameters in length, containing a charge of tumbling or cascading steel balls, pebbles, or rods.

Tube mill is a revolving cylinder of up to five diameters in length used for fine pulverization of ore, rock, and other such materials; the material, mixed with water, is fed into the chamber from one end, and passes out the other end as slime.

II - Ring and Ball

This type consists of two rings separated by a series of large balls. The lower ring rotates, while the upper ring presses down on the balls via a set of spring and adjuster assemblies. Coal is introduced into the center or side of the pulverizer (depending on the design) and is ground as the lower ring rotates causing the balls to orbit between the upper and lower rings. The coal is carried out of the mill by the flow of air moving through it. The size of the coal particals released from the grinding section of the mill is determined by a classifer separator. These mills are typically produced by B&W (Babcock and Wilcox).



Ash handling System.

- *Ash is the inert matter in coal and is the residue after combustion. This has to be collected and disposed off without letting it out into the atmosphere. A part of the ash, around 15 % collects as 'Bottom ash' at the bottom of the furnace. The other part collects as 'Fly ash' in the Electrostatic Precipitators. The collected ash is then transported to disposal yards or storage silos.*

Electrostatic precipitator

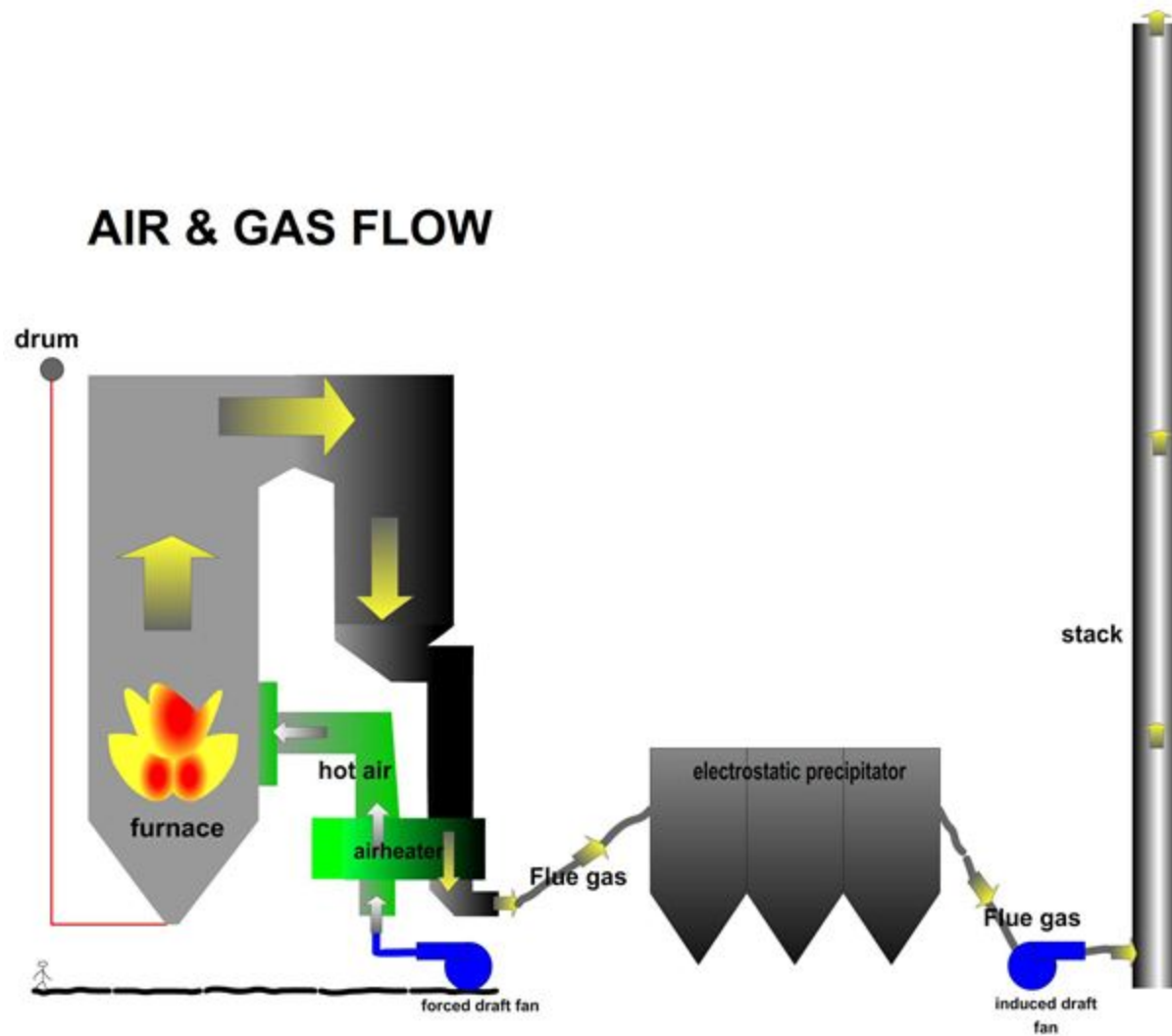
It is a device which removes dust or other finely divided particles from flue gases by charging the particles inductively with an electric field, then attracting them to highly charged collector plates. Also known as precipitator.

The process depends on two steps. In the first step the suspension passes through an electric discharge (corona discharge) area where ionization of the gas occurs. The ions produced collide with the suspended particles and confer on them an electric charge. The charged particles drift toward an electrode of opposite sign and are deposited on the electrode where their electric charge is neutralized. The phenomenon would be more correctly designated as electro deposition from the gas phase.

The use of electrostatic precipitators has become common in numerous industrial applications. Among the advantages of the electrostatic precipitator are its ability to handle large volumes of gas, at elevated temperatures if necessary, with a reasonably small pressure drop, and the removal of particles in the micrometer range. Some of the usual applications are:

- (1) removal of dirt from flue gases in steam plants.
- (2) cleaning of air to remove fungi and bacteria in establishments producing antibiotics and other drugs, and in operating rooms.
- (3) cleaning of air in ventilation and air conditioning systems (4) removal of oil mists in machine shops and acid mists in chemical process plants
- (5) cleaning of blast furnace gases
- (6) recovery of valuable materials such as oxides of copper, lead, and tin

AIR & GAS FLOW



2. Steam Generating Plant

The steam generating plant consist of boiler and its auxiliary equipments for the utilization of flue gases.

2.1 Boiler

The heat produced by the burning of coal in the boiler is used to produce steam at high temperature and pressure. The flue gases produced at the time of combustion is passed through the super heater, economizer, air pre-heater and finally exhausted into the atmosphere through chimney.

2.2 Super Heater

The steam produced in the boiler has got moisture content so it is dried and superheated (ie steam temperature is increased above boiling point of water)by the flue gases on the way to chimney. Super heating ensures two benefits at first the overall efficiency of the system is increased and secondly the corrosion to the turbine blades due to condensation in later stages is prevented. The superheated steam from super-heater is fed to steam turbine by means of a main valve.

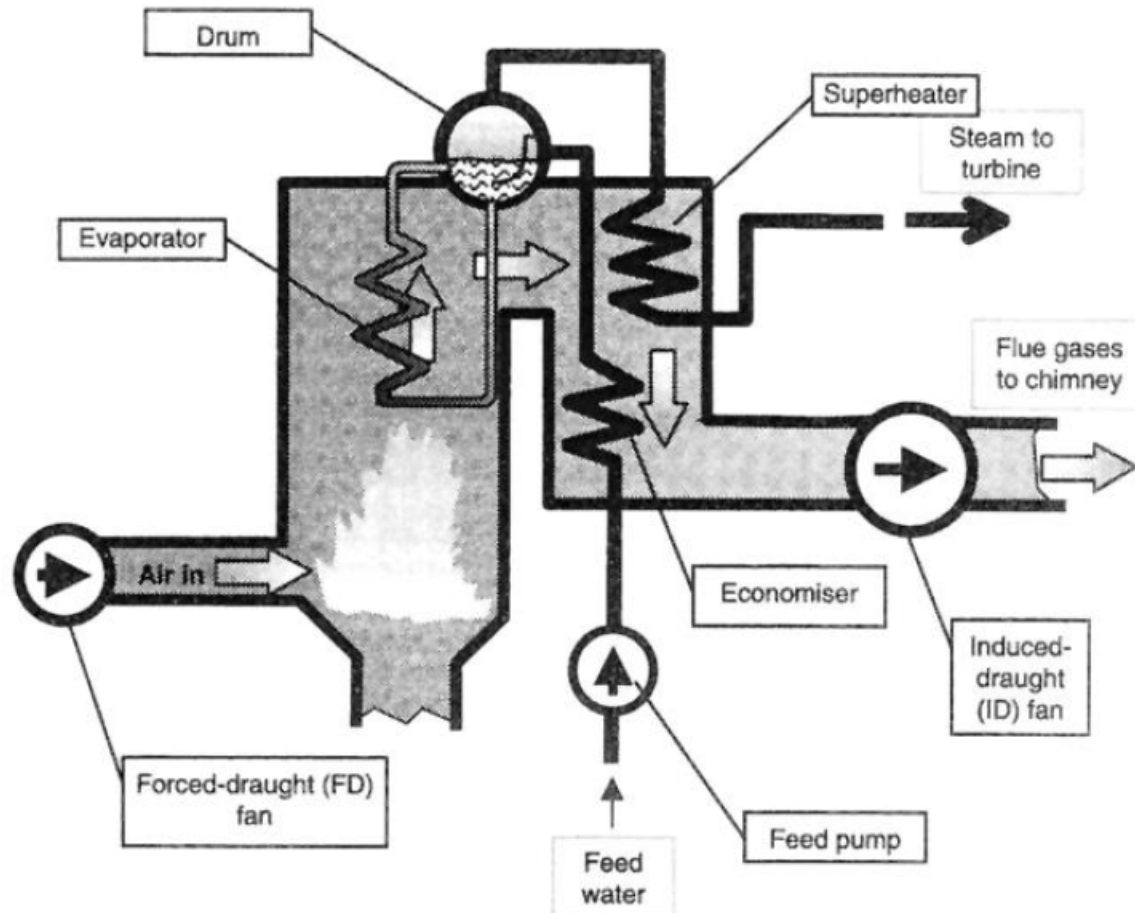
2.3 Economizer

Economizer is a feed water heater. It uses the heat produced by the flue gases for this purpose. The feed water is passed through the economizer before supplying it to the boiler and economizer absorbs a part of heat from the flue gas to increase the temperature of the feed water.

2.4 Air pre-heater

Air pre-heater increases the temperature of the air supplied to coal for combustion using flue gases. Air is drawn in using a forced draught fan and is passed through pre-heater before supplying it to the boiler. This process increases the thermal efficiency and steam capacity per square meter of the boiler surface.

Schematic steam generator



Types of steam

As shown in the diagram below, there are three types of steam:

Wet steam: A mixture of water plus steam (liquid plus vapor) at the boiling point temperature of water at a given pressure. Quality of steam refers to the fraction or percentage of gaseous steam in a wet steam mixture.

Dry steam: Steam, at the given pressure, that contains no water (also referred to as **saturated steam**). The steam quality = 100%. At the top of steam generator units for producing saturated steam, there are moisture separators used to remove residual water droplets from outgoing steam.

Superheated steam: Dry steam, at the given pressure, that has been heated to a temperature higher than the boiling point of water at that pressure.

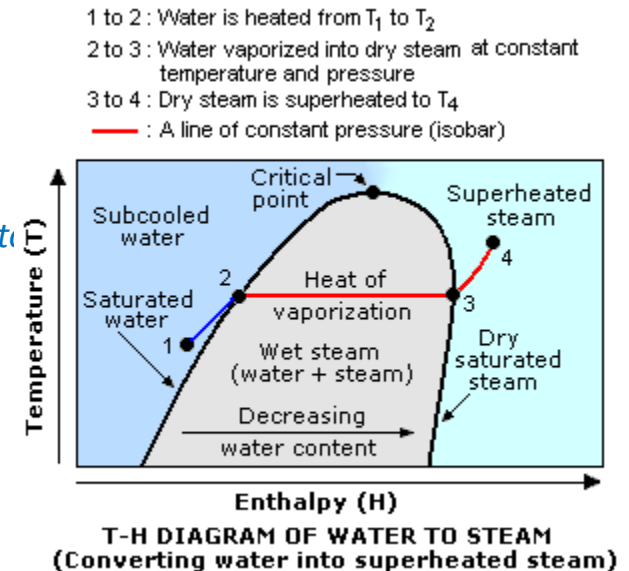
Referring to the adjacent drawing again, water is converted into **wet, dry saturated or superheated steam** in three steps:

I - Water at point 1 is heated to its boiling point at the given pressure of point 2 (the dark blue line). At that point the water is then referred to as **saturated water**. The amount of heat added between points 1 and 2 is called **sensible heat**.

II - The water is further heated at constant pressure (the red isobar from point 2 to point 3) to form **wet steam**. When it is completely vaporized (at point 3), it is then **dry saturated steam**. The amount of heat required to completely vaporize the water is called the heat of vaporization and denoted as H_v or H_{vap} .

III - The dry saturated steam is yet further heated at constant pressure (the red isobar from point 3 to point 4). The steam is then referred to as **superheated steam**. The amount of heat added to superheat the dry saturated steam is also called **sensible heat**.

It should be noted that the points 2 and 3 are at the same boiling point temperature and pressure and also that, at those conditions, the liquid and the steam (whether wet or dry) are in equilibrium with each other.



Superheater

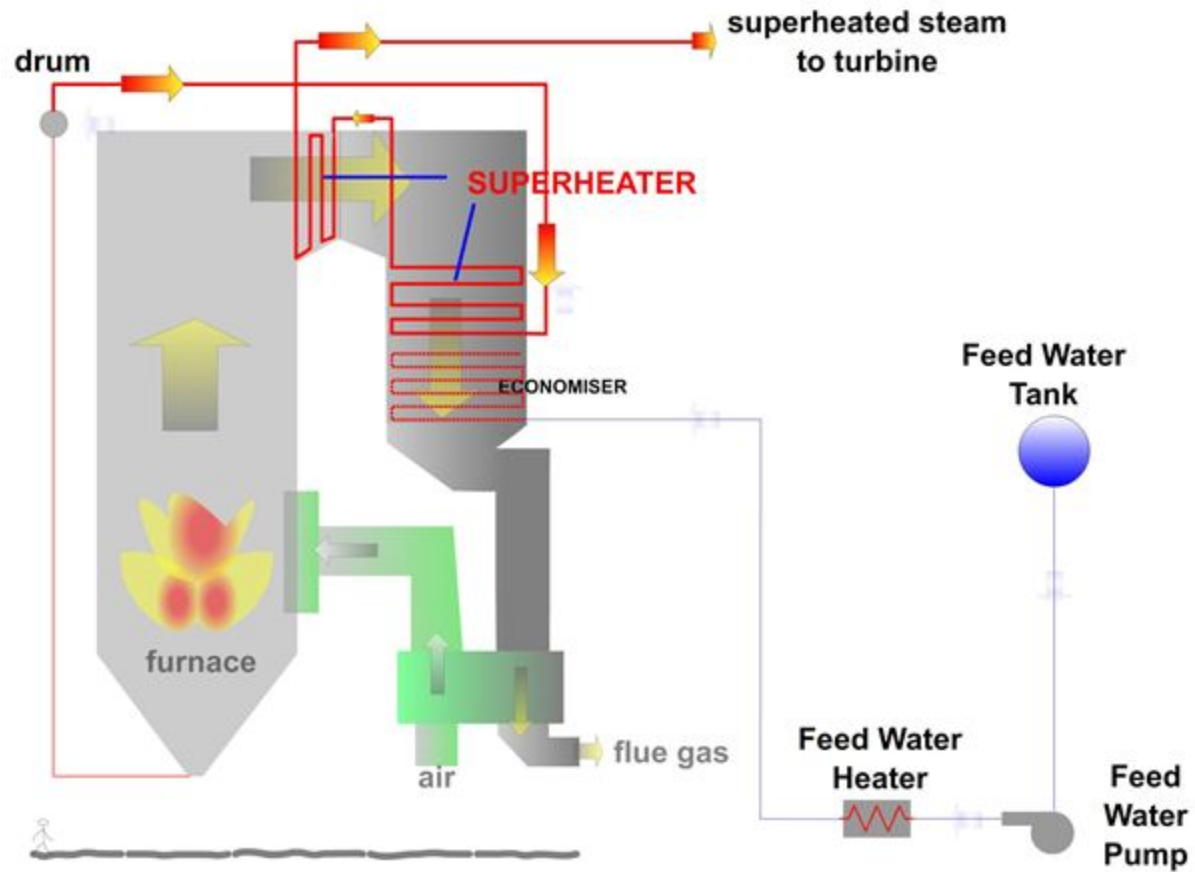
A greater quantity of steam can be generated from a given quantity of water by superheating it. As the fire is burning at a much higher temperature than the saturated steam it produces, far more heat can be transferred to the once-formed steam by superheating it and turning the water droplets suspended therein into more steam and greatly reducing water consumption.

The superheater works like coils on an air conditioning unit, however to a different end. The steam piping (with steam flowing through it) is directed through the flue gas path in the boiler furnace. This area typically is between 1,300–1,600 degree [Celsius](#) (2,372–2,912 [°F](#)). Some superheaters are radiant type (absorb heat by radiation), others are convection type (absorb heat via a fluid i.e. gas) and some are a combination of the two. So whether by convection or radiation the extreme heat in the boiler furnace/flue gas path will also heat the superheater steam piping and the steam within as well.

It is important to note that while the temperature of the steam in the superheater is raised, the pressure of the steam is not: the turbine or moving pistons offer a "continuously expanding space" and the pressure remains the same as that of the boiler.

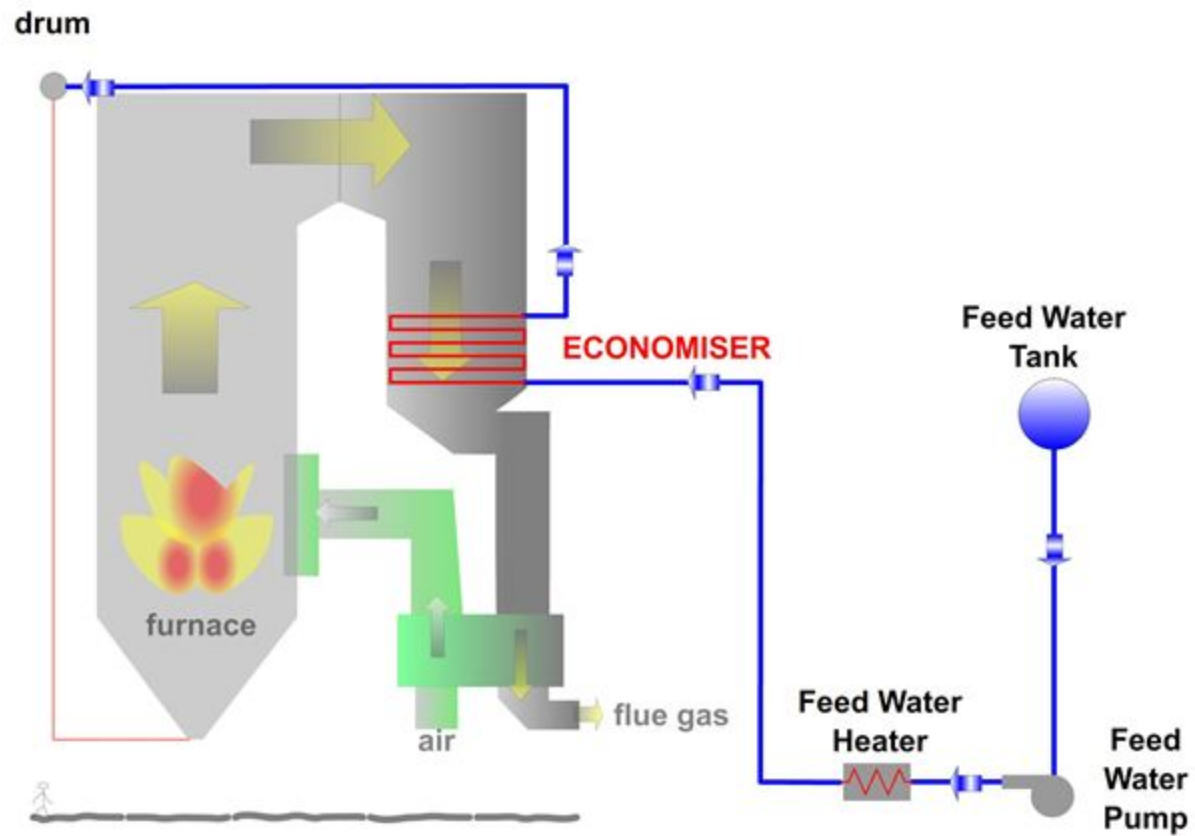
The process of superheating steam is most importantly designed to remove all droplets entrained in the steam to prevent damage to the turbine blading and/or associated piping. Superheating the steam expands the volume of steam, which allows a given quantity (by weight) of steam to generate more power.

When the totality of the droplets are eliminated, the steam is said to be in a superheated state.



Economizer

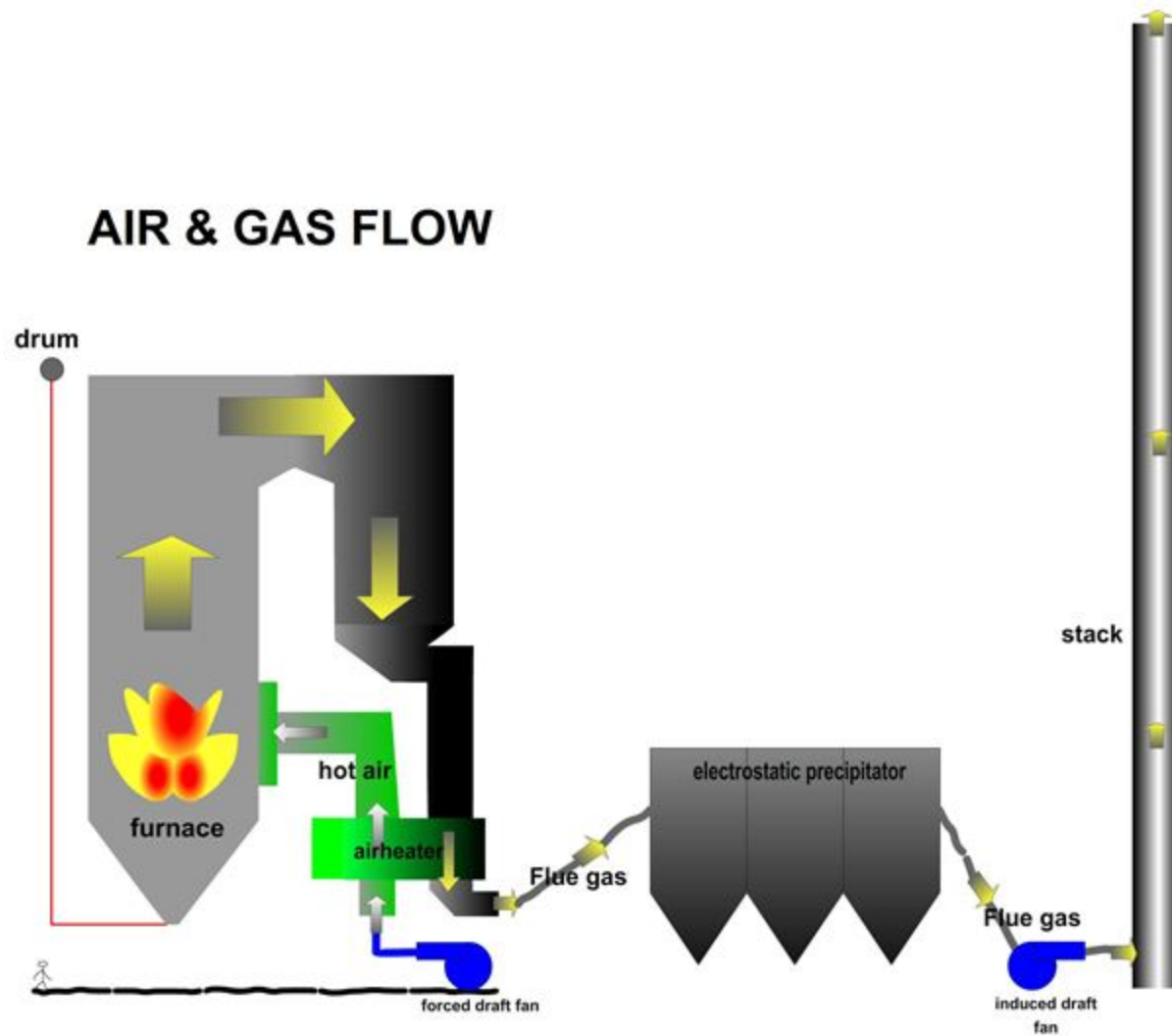
- *Flue gases coming out of the boiler carry lot of heat. The function of economizer is to recover some of the heat from the heat carried away in the flue gases up the flue gas stack and utilize it for heating the feed water to the boiler. It is placed in the passage of flue gases in-between the exit from the boiler and the entry to the chimney.*
- *The use of economizer results in saving in coal consumption , increase in steaming rate and high boiler efficiency but needs extra investment and increase in maintenance costs and floor area required for the plant. This is used in all modern plants. In this a large number of small diameter thin walled tubes are placed between two headers. Feed water enters the tube through one header and leaves through the other. The flue gases flow out side the tubes usually in counter flow.*



Air preheater

- *The remaining heat of flue gases is utilized by air preheater. It is a device used in steam boilers to transfer heat from the flue gases to the combustion air before the air enters the furnace. Also known as air heater , air-heating system. It is kept at a place near by where the air enters in to the boiler.*
- *The purpose of the air preheater is to recover the heat from the flue gas from the boiler to improve boiler efficiency by burning warm air which increases combustion efficiency, and reducing useful heat lost from the flue. As a consequence, the gases are also sent to*
- *the chimney or stack at a lower temperature, allowing simplified design of the ducting and stack. It also allows control over the temperature of gases leaving the stack (to meet emissions regulations, for example).After extracting heat flue gases are passed to electrostatic precipitator.*

AIR & GAS FLOW



Economizer and Air Pre-Heaters are Provided for Heat Recovery

Boilers are provided with economizer and air pre-heaters to recover heat from the flue gases. An increase of about 20% in boiler efficiency is achieved by providing both economizer and air pre-heaters. If a economizer alone is provided then the efficiency will increase by 8% only.

Most of the high capacity boilers firing coal operate with an efficiency of around 86% on the Higher Heat Value basis. Loss of around 14% can be attributed to various losses of which the dry gas loss is about 35% of the total. When both economizers and air pre-heaters are not provided the boiler efficiency drops to around 66% from 86%. When air pre-heater is not provided the boiler efficiency will be around 74 % only. Thus we can conserve about 20% extra fuel when we provide both economizers and air pre-heaters in boilers.

Economizer

The feed water from the high pressure heaters enters the economizer and picks up heat from the flue gases after the low temperature superheater. Many types of economizer are designed for picking up heat from the flue gas. These can be classified as an inline or staggered arrangement based on the type of tube arrangement. The staggered arrangement is compact and occupies less volume for the same amount of heat transfer when compared to the inline arrangement. Economizers are also designed with plain tube and finned tubes. The fins can be longitudinal or spiral. All these types are suitable for clean fuels like gas, oil, and low ash coals. For high ash coals, only the plain tube inline arrangement is used. This is mainly to reduce ash erosion and thus reduce erosion failures. These economizers pick up about 50 to 55 degrees centigrade in a large capacity boiler, which will reduce the flue gas temperature by about 150 to 170 degree centigrade. The boiler designers always keep the economizer water outlet temperature to about 25 to 35 degrees below the drum saturation temperature. This is done to mainly avoid steaming in the economizer. A steaming economizer generally is less reliable. As a rule of thumb, for every one degree pick up of economizer water temperature, there will be a drop of about 3 to 3.5 degrees.

Air pre heaters

Air pre-heaters are provided in boilers to preheat the combustion air. There are two main types: recuperative and regenerative air heaters.

Tubular or recuperative air pre-heaters are provided in boilers of medium and small range of steam generation. This type of air pre-heater becomes very large in size if they have to be used in very high capacity boilers like 600 tons/hr of steam production and above. In these cases regenerative air pre-heaters are used. The arrangement of all these air pre-heaters differ with the design and, in large, the way they are combined for very high capacity boilers. Regenerative air pre-heaters are compact and can have a stationary or rotating hood. A combination of tubular and regenerative type of air pre-heaters is used in very high capacity boilers. The tubular being used for primary air heating and the regenerative used for the secondary air heating. In case the boiler designers do not want to go for a combination of tubular and regenerative air pre-heater, then they have a choice of tri-sector regenerative air heater. Normally the ambient air is heated to about 300 to 350 degree centigrade. This results in a flue gas temperature drop of around 230 to 250 degree centigrade. So for each degree pick up in air temperature, roughly 0.8 degree drop in flue gas temperature is achieved.

Steam coil air pre-heaters are another type. These are used only during start up of the boiler to prevent low temperature corrosion. This air heater does not contribute to improving the efficiency of boilers, but are provided to improve availability. It is seen that during start up the chances of low temperature corrosion is high, and hence the need to provide the steam coil air heaters is evident.

Both economizer and air pre-heaters are called heat recovery systems in a boiler. Were it not for these heat recovery systems, present day boilers would be operating at much lower efficiency levels.

Deaerator

is a device that is widely used for the removal of air and other dissolved gases from the feedwater to steam-generating boilers.

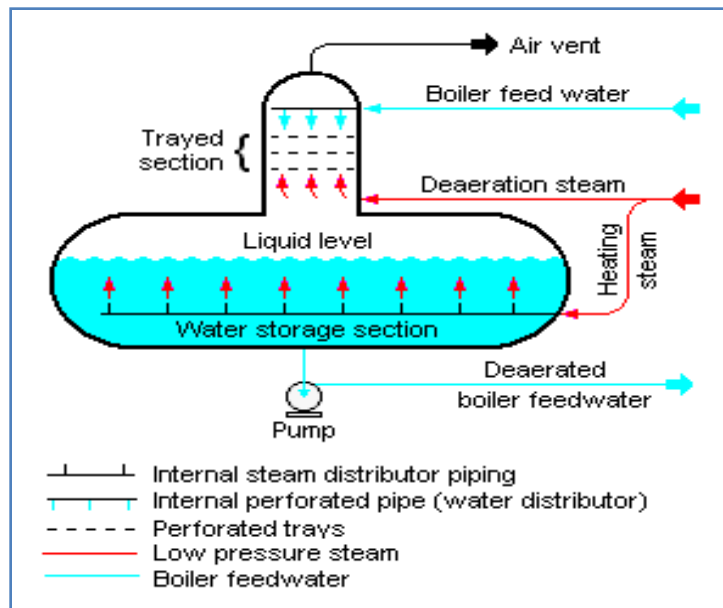
In particular, dissolved oxygen in boiler feedwaters will cause serious corrosion damage in steam systems by attaching to the walls of metal piping and other metallic equipment and forming oxides (rust).

Water also combines with any dissolved carbon dioxide to form carbonic acid that causes further corrosion.

Most deaerators are designed to remove oxygen down to levels of 7 ppb by weight ($0.0005 \text{ cm}^3/\text{L}$) or less.

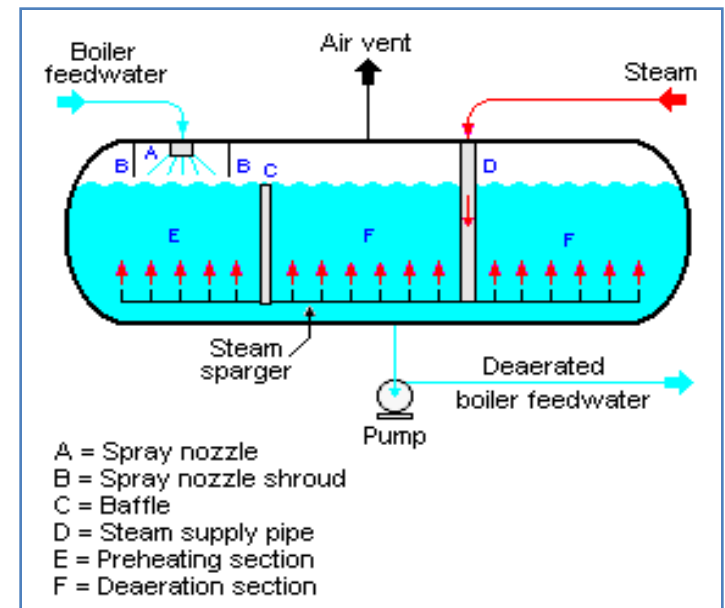
There are two basic types of deaerators ,

1. the tray-type
2. the spray-type



tray-type or cascade-type

includes a vertical domed deaeration section mounted on top of a horizontal cylindrical vessel which serves as the deaerated boiler feedwater storage tank .



The spray-type

consists only of a horizontal (or vertical) cylindrical vessel which serves as both the deaeration section and the boiler feedwater storage tank.

Feedwater heater

is a power plant component used to pre-heat water delivered to a steam generating boiler. Preheating the feedwater reduces the irreversibilities involved in steam generation and therefore improves the thermodynamic efficiency of the system. This reduces plant operating costs and also helps to avoid thermal shock to the boiler metal when the feedwater is introduced back into the steam cycle.

It should be noted that the energy used to heat the feedwater is usually derived from steam extracted between the stages of the steam turbine. Therefore, the steam that *would be used* to perform expansion work in the turbine (and therefore generate power) is not utilized for that purpose. The percentage of the total cycle steam mass flow used for the feedwater heater is termed the extraction fraction^[4] and must be carefully optimized for maximum power plant thermal efficiency since increasing this fraction causes a decrease in turbine power output.

Feedwater heaters can also be *open* and *closed* heat exchangers.

Many power plants incorporate a number of feedwater heaters and may use both open and closed components.

An economizer serves a similar purpose to a feedwater heater, but is technically different. Instead of using actual cycle steam for heating, it uses the lowest-temperature flue gas from the furnace to heat the water before it enters the boiler proper. This allows for the heat transfer between the furnace and the feedwater to occur across a smaller average temperature gradient (for the steam generator as a whole). System efficiency is therefore further increased when viewed with respect to actual energy content of the fuel.

Open & closed FWH

- *An open feedwater heater is merely a direct-contact heat exchanger in which extracted steam is allowed to mix with the feedwater. This kind of heater will normally require a feed pump at both the feed inlet and outlet since the pressure in the heater is between the boiler pressure and the [condenser](#) pressure. A [deaerator](#) is a special case of the open feedwater heater which is specifically designed to remove non-condensable gases from the feedwater.*
- *Closed feedwater heaters are typically [shell and tube heat exchangers](#) where the feedwater passes throughout the tubes and is heated by turbine extraction steam. These do not require separate pumps before and after the heater to boost the feedwater to the pressure of the extracted steam as with an open heater. However, the extracted steam (which is most likely almost fully condensed after heating the feedwater) must then be throttled to the condenser pressure, an [isenthalpic](#) process that results in some [entropy](#) gain with a slight penalty on overall cycle efficiency*

Flue gas stack (chimney)

A chimney is a structure for venting hot flue gases or smoke from a boiler, stove, furnace or fireplace to the outside atmosphere.

Chimneys are typically vertical, or as near as possible to vertical, to ensure that the gases flow smoothly, drawing air into the combustion in what is known as the stack, or chimney, effect.

The space inside a chimney is called a flue.

Chimneys may be found in buildings, steam locomotives and ships. In the US, the term smokestack (stack) is also used when referring to locomotive chimneys.

The term funnel is generally used for ship's chimneys and sometimes to refer to locomotive chimneys..

Chimneys are tall to increase their draw of air for combustion and to disperse pollutants in the flue gases over a greater area so as to reduce the pollutant concentrations in compliance with regulatory or other limits.

3.Steam Turbine

- The dry and super heated steam from super-heater is fed to the turbine by means of a main valve.
- Due to the striking or reaction impact of the steam on the blades of turbine it starts rotating ie heat energy is converted to mechanical energy.
- After giving heat energy to the turbine the steam is exhausted to a condenser which condenses the exhausted steam by means of a cold water circulation.



4.Alternator

- The steam turbine is coupled to an alternator the alternator converts the mechanical energy into electrical energy.
- The electrical output is transferred to the bus bars through transformer, circuit breaker and isolators.

5.Feed Water

- The condensed water produced in the condenser is used as feed water.
- some amount of water may be lost in the cycle but it is compensated using an external source and the cycle repeats and gives a better efficiency to the system.

6. Cooling Arrangement

- In order to increase the efficiency of the plant the steam coming from the turbine is condensed using a condenser. The water circulation for cooling steam in condenser is take from a natural source like river, stream etc and the out coming hot water from condenser is discharged in some lower portion of the water source.
- In scarcity of water the water from the condenser is cooled and reused with the help of a cooling tower.

Chapter one

Power plant fundamentals

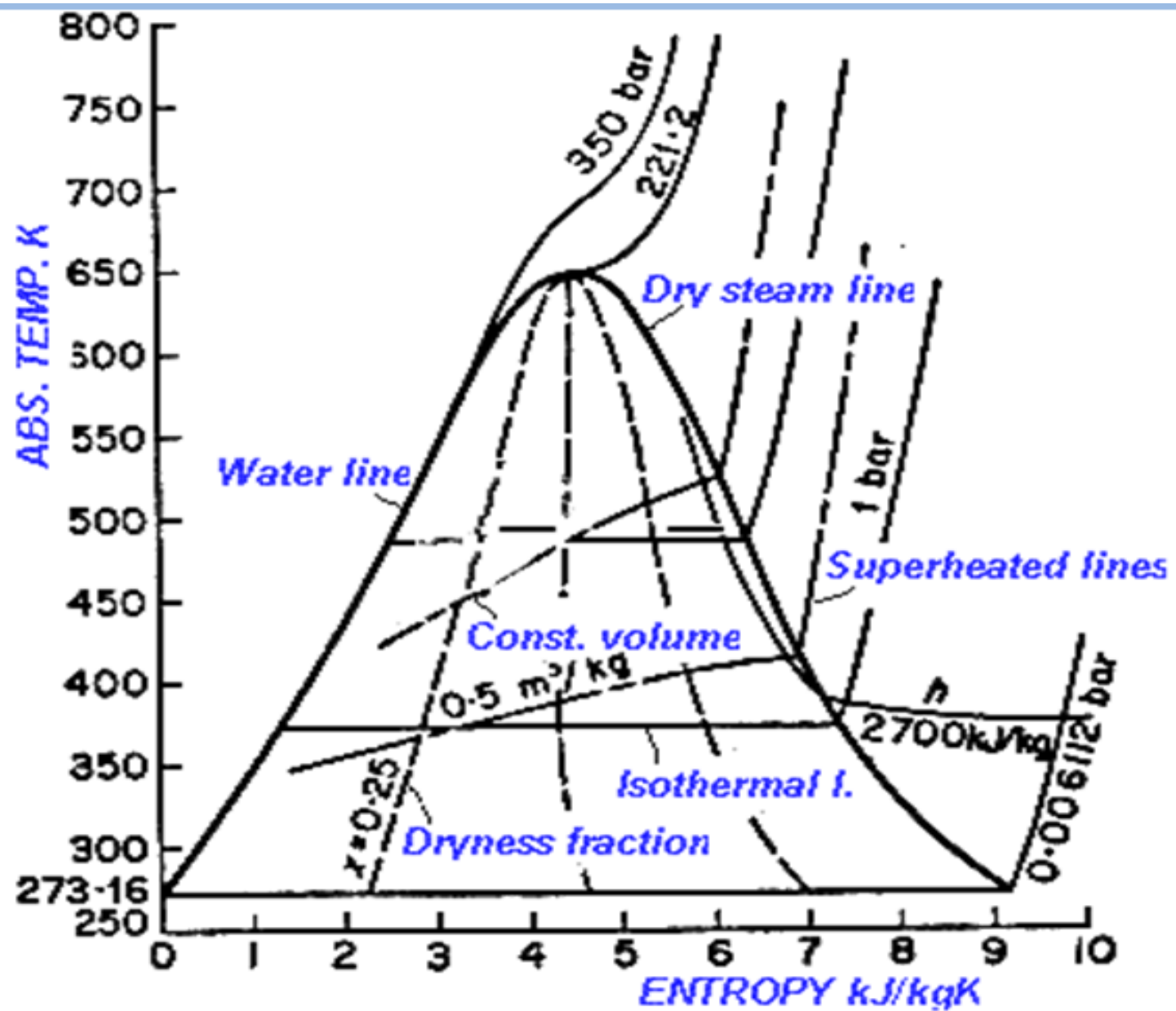
1.04 – thermodynamic
charts & diagrams

Charts & diagrams

- There are quite number of charts & diagrams associated with engineering science, all of which related in some extent to steam tables or other related specific constants, factors, or coefficients. However, the most widely related to power plant engineering are the followings:
 1. T-s diagram.
 2. h-s diagram.
 3. T-h diagram.
 4. P-h diagram

1 / T – s diagram

- The entropy diagram for steam is often convenient because it shows the relationship between
 - *Pressure*
 - *Temperature*
 - *Dryness Fraction*
 - *Entropy*
- With two of the factors given - the others can be found in the diagram. The ordinates in the diagram represents the Entropy and the Absolute temperature.



The diagram consist of the following lines

1. *Isothermal line*
2. *Pressure lines*
3. *Lines of dryness fraction*
4. *Waterline between water and steam*
5. *Dry steam lines*
6. *Constant volume lines*

An adiabatic expansion is a vertical line. An adiabatic process is expansion at constant entropy with no transfer of heat.

Critical temperature of steam is 375 to 3,380°C

Critical pressure is 217.8 atm

To produce 100% dry steam in an boiler, and keep the steam dry throughout the piping system, is in general not possible. Droplets of water will escape from the boiler surface. Because of turbulence and splashing when bubbles of steam break through the water surface the steam space will contain a mixture of water droplets and steam. In addition heat loss in the pipes will condensate steam to droplets of water.

Steam - produced in a boiler where the heat is supplied to the water and where the steam are in contact with the water surface of the boiler - will contain approximately 5% water by mass.

Dryness fraction of Wet Steam

- If the water content of the steam is 5% by mass, then the steam is said to be 95% dry and has a dryness fraction of 0.95.
- Dryness fraction can be expressed as:
- $\zeta = w_s / (w_w + w_s) \quad (1)$
- *where*
- $\zeta = \text{dryness fraction}$
- $w_w = \text{mass of water (kg)}$
- $w_s = \text{mass of steam (kg)}$

Enthalpy of Wet Steam

- The actual enthalpy of evaporation of wet steam is the product of the dryness fraction - ζ - and the [specific enthalpy](#) - h_s - from the [steam tables](#). Wet steam have lower usable heat energy than dry saturated steam.
- $$h_t = h_s \zeta + (1 - \zeta) h_w \quad (2)$$
- *where*
- h_t = *enthalpy of wet steam (kJ/kg)*
- h_s = *enthalpy of steam (kJ/kg)*
- h_w = *enthalpy of saturated water or condensate (kJ/kg)*

Specific Volume of Wet Steam

- The droplets of water in wet steam will occupy negligible space in the steam and the specific volume of wet steam will be reduced according to the dryness fraction.
- $v = v_s \zeta \quad (3)$
- *where*
- $v = \text{specific volume of wet steam (m}^3/\text{kg)}$
- $v_s = \text{specific volume of the dry steam (m}^3/\text{kg)}$

Example

Enthalpy and Specific Volume of Wet Steam

- Steam at pressure 5 bar gauge has a dryness fraction of 0.95.

- Total enthalpy can be expressed as:

- $$h_t = (2085 \text{ kJ/kg}) 0.95 + (1 - 0.95) (670.4 \text{ kJ/kg})$$
$$= \underline{2,014} \text{ kJ/kg}$$

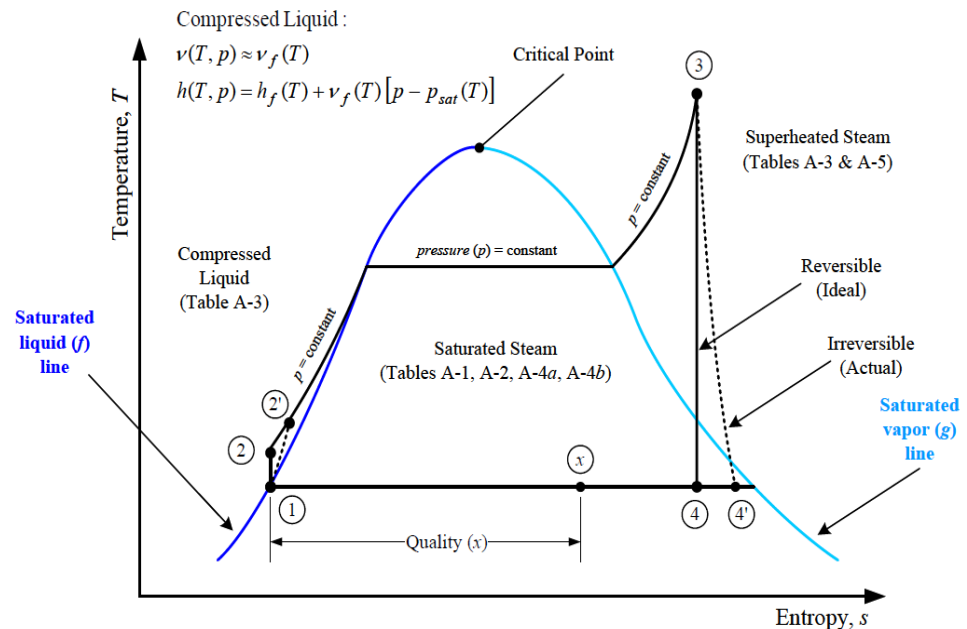
- Specific volume can be expressed as:

- $$v = (0.315 \text{ m}^3/\text{kg}) 0.95$$
$$= \underline{0.299} \text{ m}^3/\text{kg}$$

Rankine cycle

Temperature-Entropy Diagram

- A temperature-entropy diagram is shown opposite.
- The dark blue line represent saturated water line, and the light blue saturated vapor line, meeting at the critical point forming a dome shape
- Within the dome shape is the water-steam mixture region, where constant (P & T) evaporation takes place.
- The non-ideal nature of expansion takes the working fluid to the point (4⁻) after expansion.

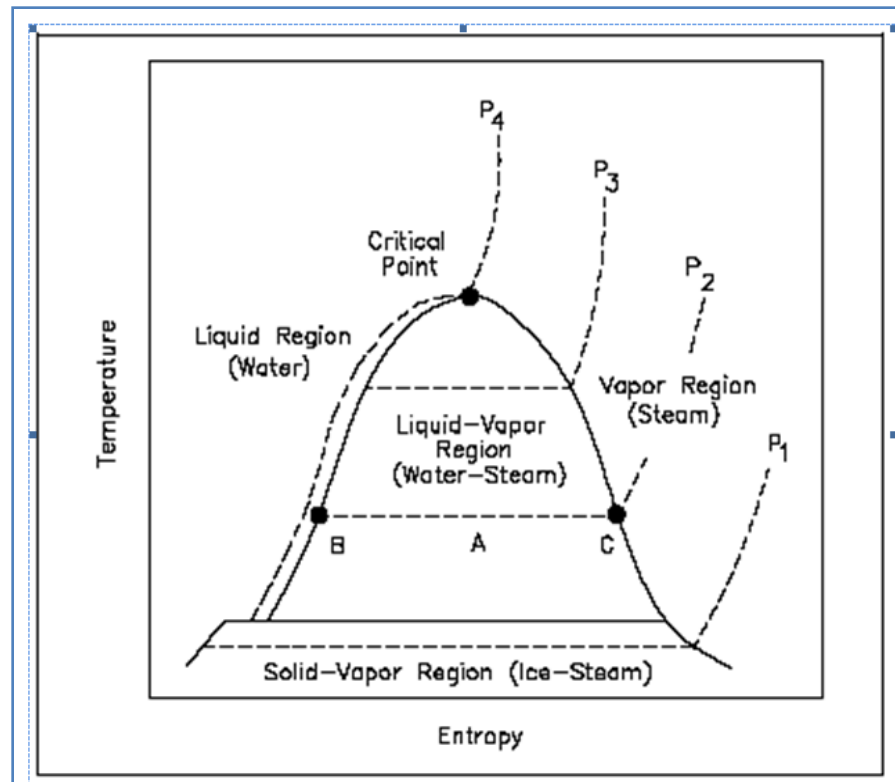


T-s diagram is the type of diagram most frequently used to analyze energy transfer system cycles.

This is because the work done by or on the system and the heat added to or removed from the system can be visualized on the T-s diagram.

By the definition of entropy, the heat transferred to or from a system equals the area under the T-s curve of the process.

This Figure is the T-s diagram for pure water. A T-s diagram can be constructed for any pure substance.



In the water-vapor region in Figure above, water and steam exist together. For example at point (A) water with an entropy (s_f) given by point (B), exists together with steam with an entropy (s_g) given by point C. The quality of the mixture at any point in the water-vapor region can be found using the following relationship.

$$s = xs_g + (1 - x)s_f$$

$$x = \frac{s - s_f}{s_{fg}}$$

where:

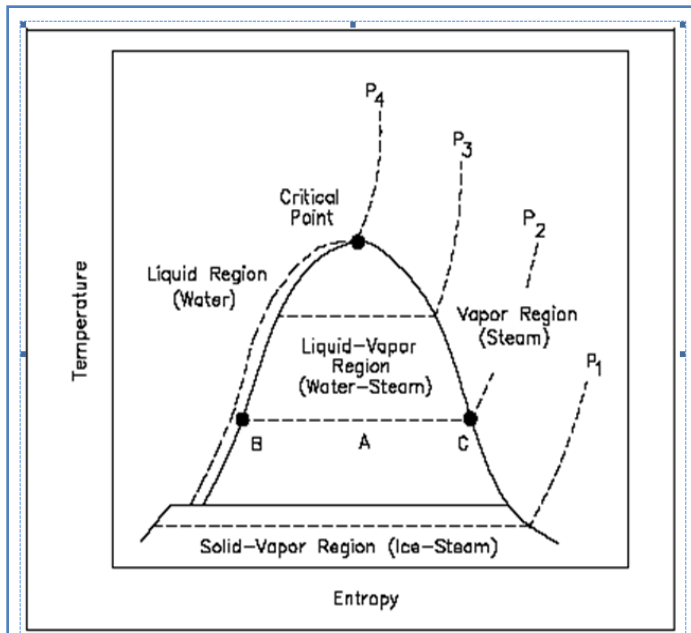
s = specific entropy of the mixture (Btu/lbm-°R)

x = quality of the mixture (no units)

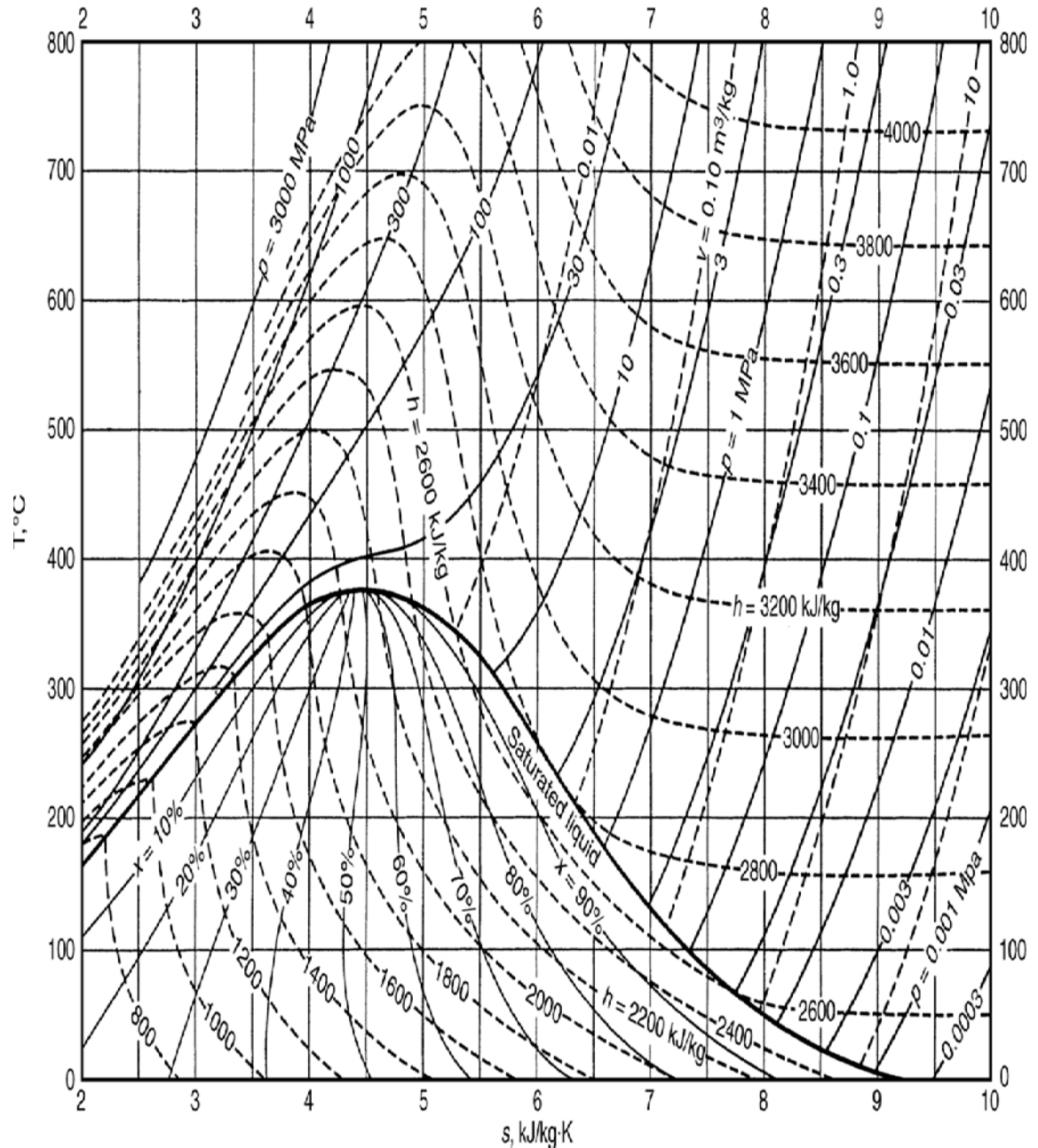
s_g = specific entropy of the saturated vapor (Btu/lbm-°R)

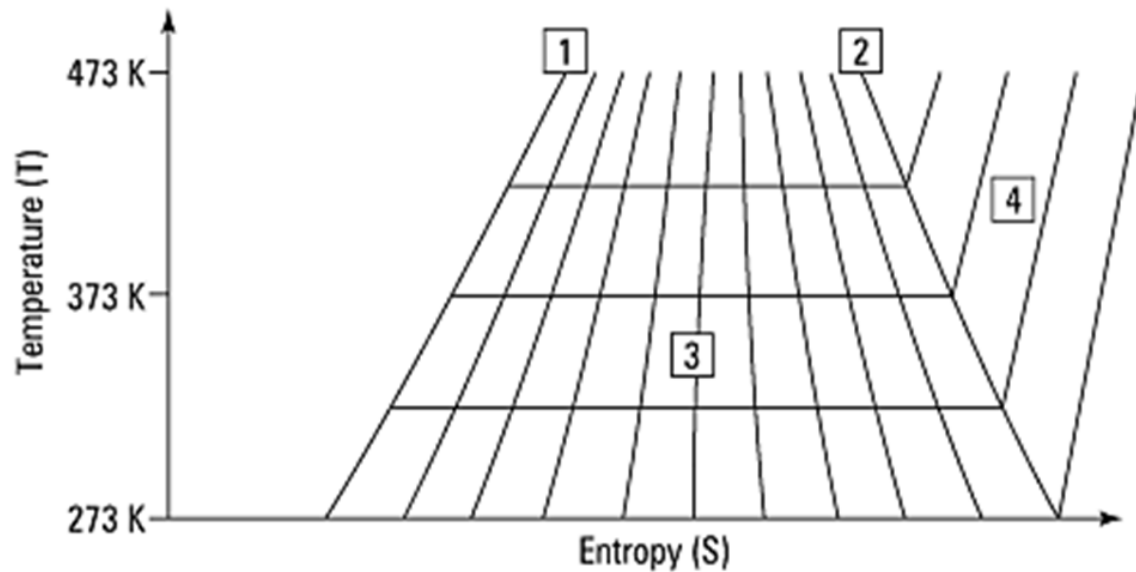
s_f = specific entropy of the saturated liquid (Btu/lbm-°R)

s_{fg} = specific entropy change of vaporization (Btu/lbm-°R) or $s_{fg} = s_g - s_f$



The horizontal distance between the saturated water line and the dry saturated steam line represents the amount of latent heat or enthalpy of evaporation, and is called the evaporation line; (enthalpy of evaporation decreases with rising pressure). The area to the right of the dry saturated steam line is the superheated steam region, and lines of constant pressure now curve upwards as soon as they cross the dry saturated steam line.





The diagram produced showing temperature against entropy would look something like that in above Figure, where:

1 is the saturated water line.

2 is the dry saturated steam line.

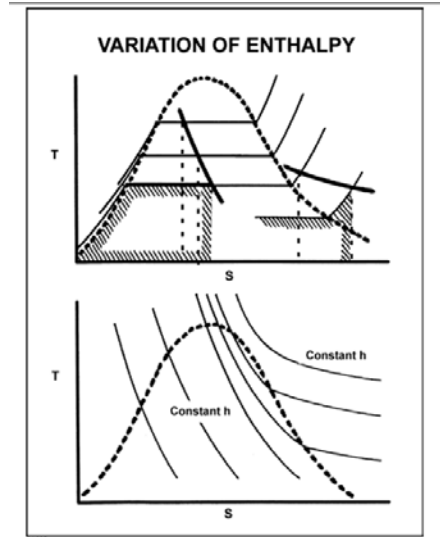
3 are constant dryness fraction lines in the wet steam region.

4 are constant pressure lines in the superheat region.

What use is the temperature - entropy diagram (or T - S diagram)?

One potential use of the T - S diagram is to follow changes in the steam condition during processes occurring with no change in entropy between the initial and final state of the process. Such processes are termed Isentropic (constant entropy).

Unfortunately, the constant total heat lines shown in a T - S diagram are curved, which makes it difficult to follow changes in such free and unrestricted expansions as those when steam is allowed to flow through and expand after a control valve. In the case of a control valve where the velocities in the connecting upstream and downstream pipes are near enough the same, the overall process occurs with constant enthalpy (isenthalpic). In the case of a nozzle, where the final velocity remains high, the overall process occurs with constant entropy.



To follow these different types of processes, a new diagram can be drawn complete with pressures and temperatures, showing entropy on the horizontal axis, and enthalpy on the vertical axis, and is called an enthalpy - entropy diagram, or H - S diagram, as shown in the next section.

2 / $h - s$ diagram “Mollier diagrams”

- The ($h - s$) diagram is also called the **Mollier diagram or Mollier chart**, named after Dr. Richard Mollier of Dresden who first devised the idea of such a diagram in 1904.
- The Mollier diagram is useful when analyzing the performance of adiabatic steady-flow processes, such as flow in nozzles, diffusers, turbines and compressors.

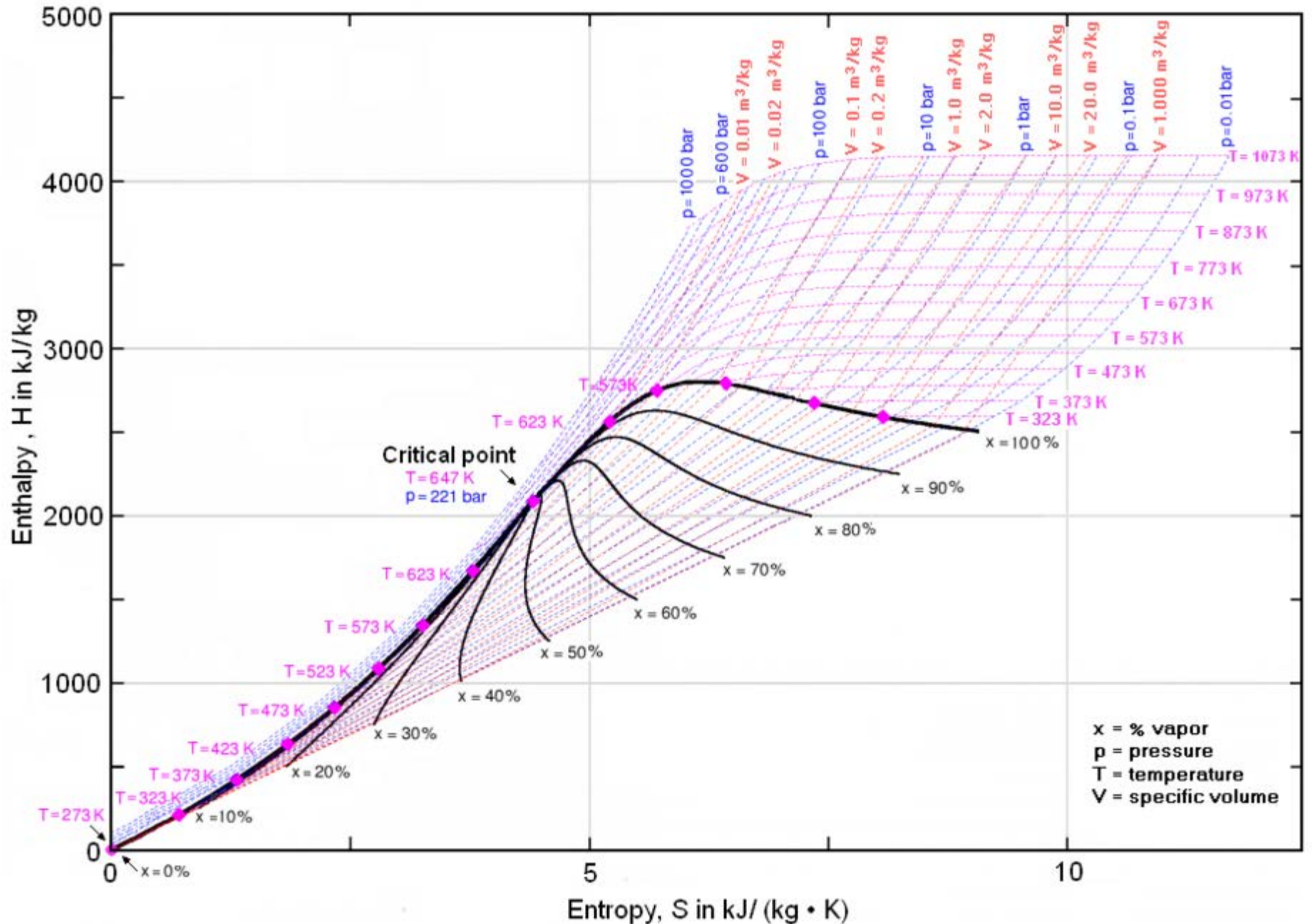
Mollier diagrams are graphical representations of the thermodynamic properties of materials involving "Enthalpy" as one of the coordinates.

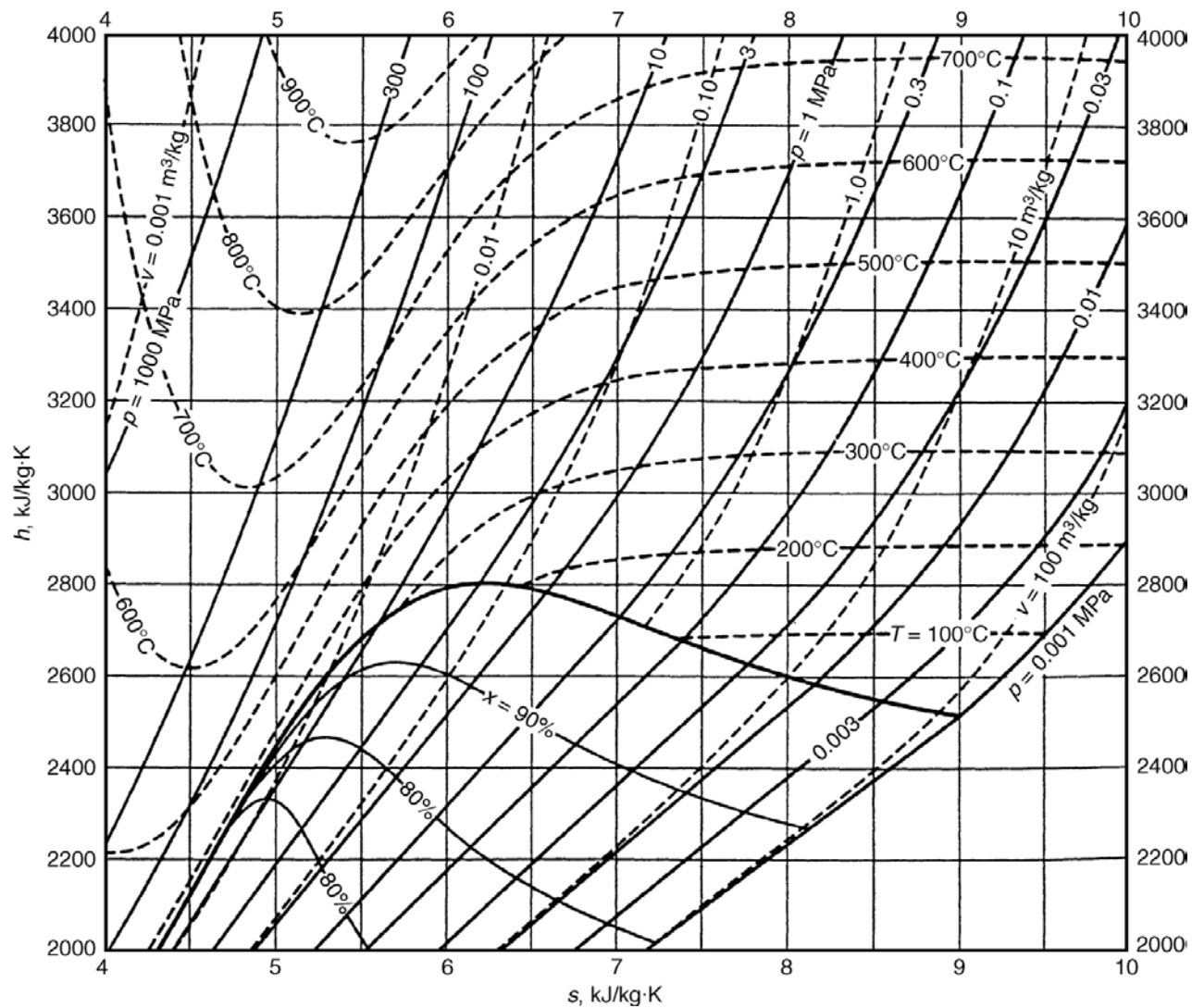
Mollier diagrams are named after [Richard Mollier](#) (1863 - 1935), a professor at [Dresden University](#) in [Germany](#), who pioneered the graphical display of the relationship of temperature, pressure, enthalpy, entropy and volume of steam (as well as for moist air) that has aided in the teaching of thermodynamics to many generations of engineers. His enthalpy-entropy (H-S) diagram for steam was first published in 1904.

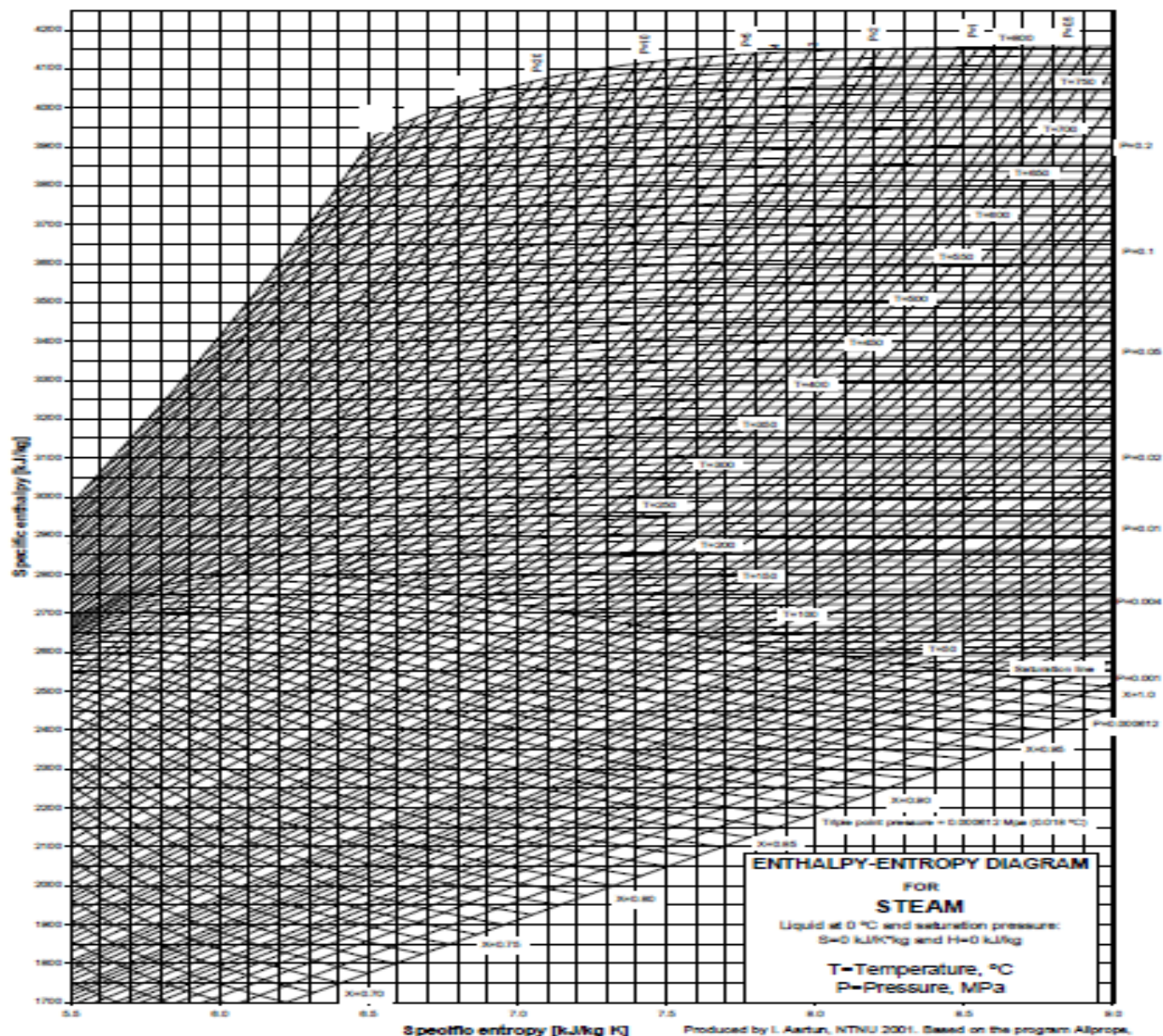
Mollier diagrams are routinely used to visualize the working cycles of thermodynamic systems involved with power plants (fossil or nuclear), gas compressors, steam turbines, refrigeration systems and air conditioning.

A samples Mollier diagram for steam is presented below and others are available online

Mollier H-S Diagram for Water-Steam



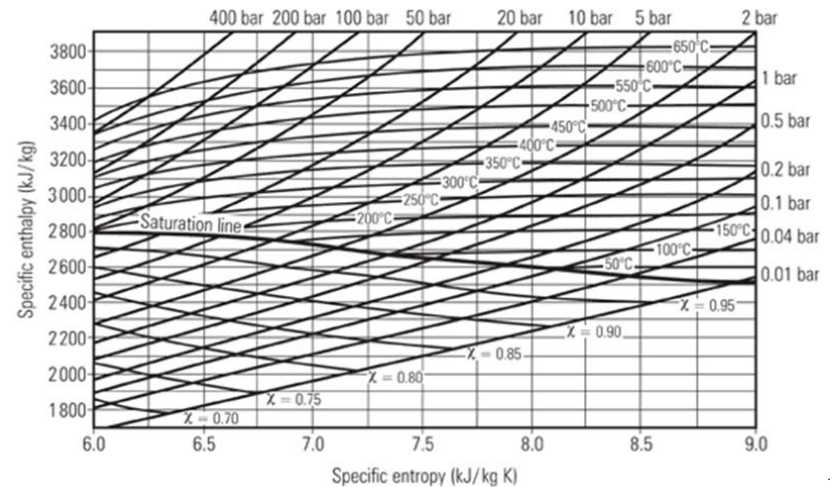


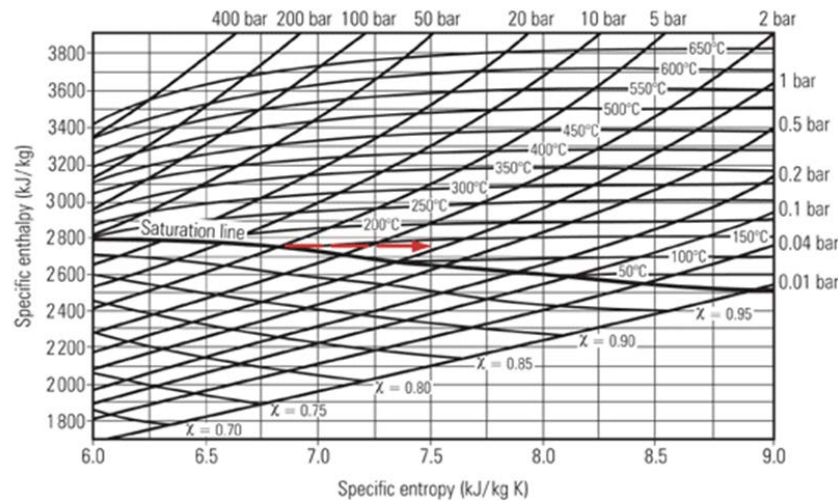


Example

using h-s diagram

- An isentropic expansion of steam is always accompanied by a decrease in enthalpy, and this is referred to as the 'heat drop' (Δh) between the initial and final condition. The (h) values can be simply read at the initial and final points on the Mollier chart, and the difference gives the heat drop.
- The accuracy of the chart is sufficient for most practical purposes.





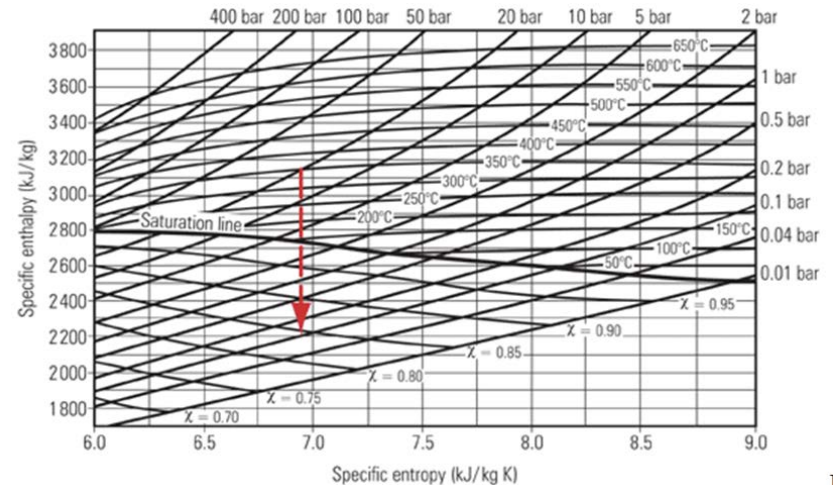
the isenthalpic expansion of steam through a control valve is simply represented by a straight horizontal line from the initial state to the final lower pressure to the right of the graph.

As the expansion through a control valve orifice is an isenthalpic process, it is assumed that the state point moves directly to the right. In fact, it does not do so directly.

For the steam to squeeze through the narrow restriction it has to accelerate to a higher speed. It does so by borrowing energy from its enthalpy and converting it to kinetic energy. This incurs a heat drop. This part of the process is isentropic; the state point moves vertically down to the lower pressure. Having passed through the narrow restriction, the steam expands into the lower pressure region in the valve outlet, and eventually decelerates as the volume of the valve body increases to connect to the downstream pipe. This fall in velocity requires a reduction in kinetic energy which is mostly re-converted back into heat and re-absorbed by the steam.

The heat drop that caused the initial increase in kinetic energy is reclaimed, and on the $H - S$ chart, the state point moves up the constant pressure line until it arrives at the same enthalpy value as the initial condition.

- the isentropic expansion of steam through a nozzle is simply a line from the initial state falling vertically to the lower final pressure, see Figure 2.15.7.



- The path of the state point is to be seen in Figure , where pressure is reduced from 5 bar at saturation temperature to 1 bar via, for example, a pressure reducing valve. Steam's enthalpy at the upstream condition of 5 bar is 2748 kJ/kg.

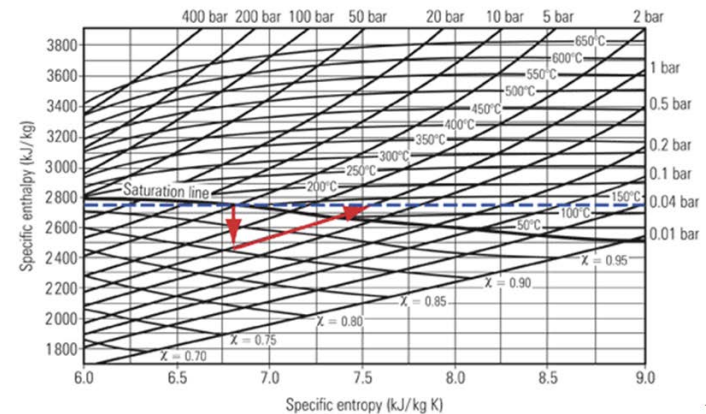
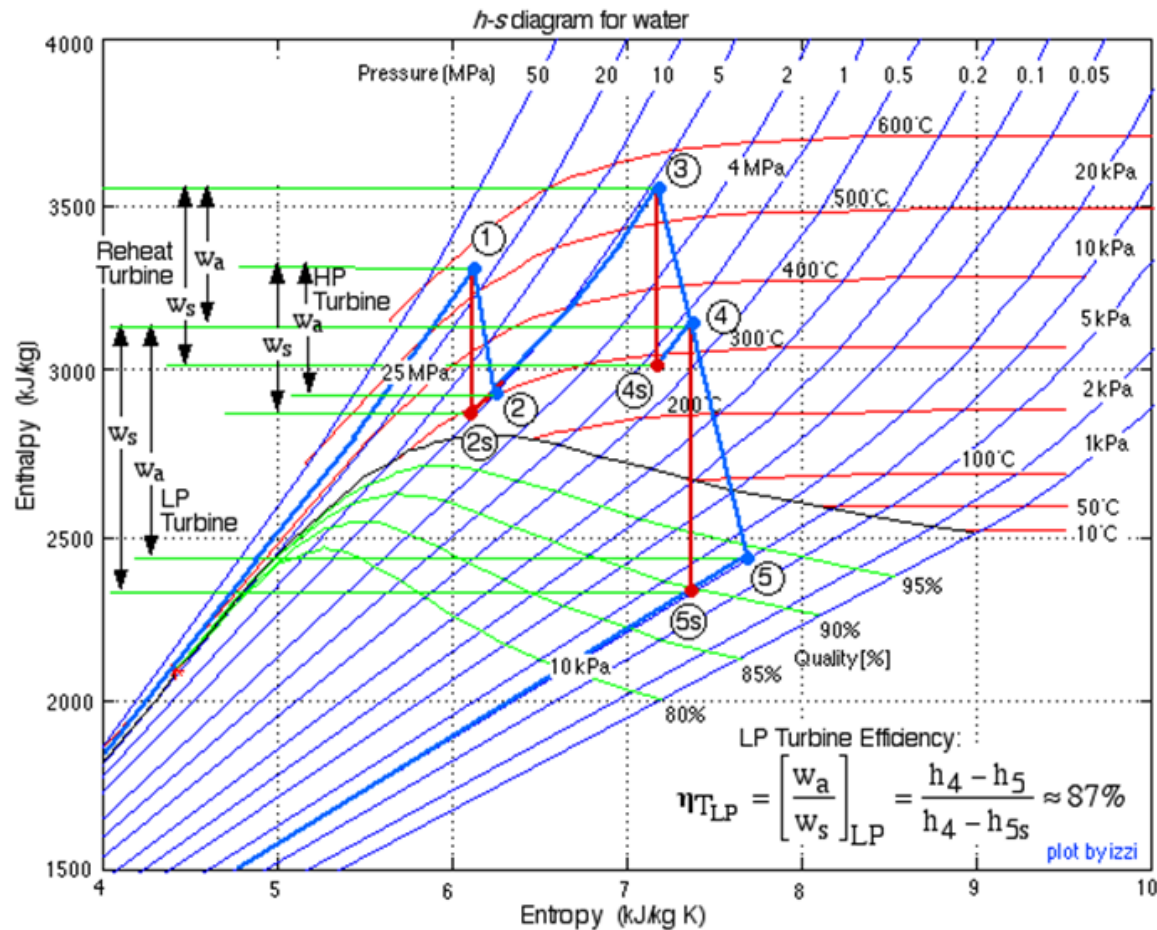


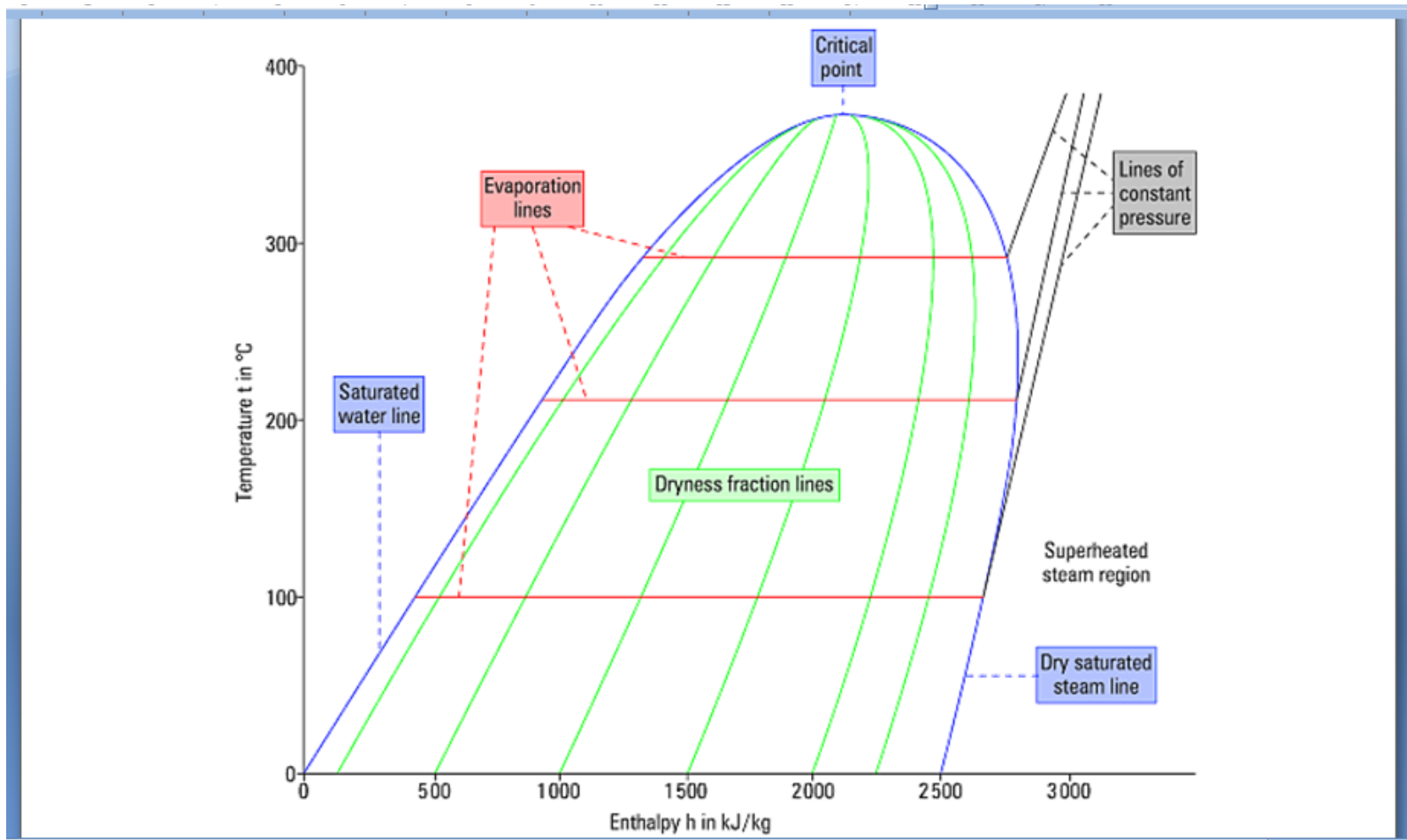
Fig.

Example

related to future sections of the course



3 / T – h diagram

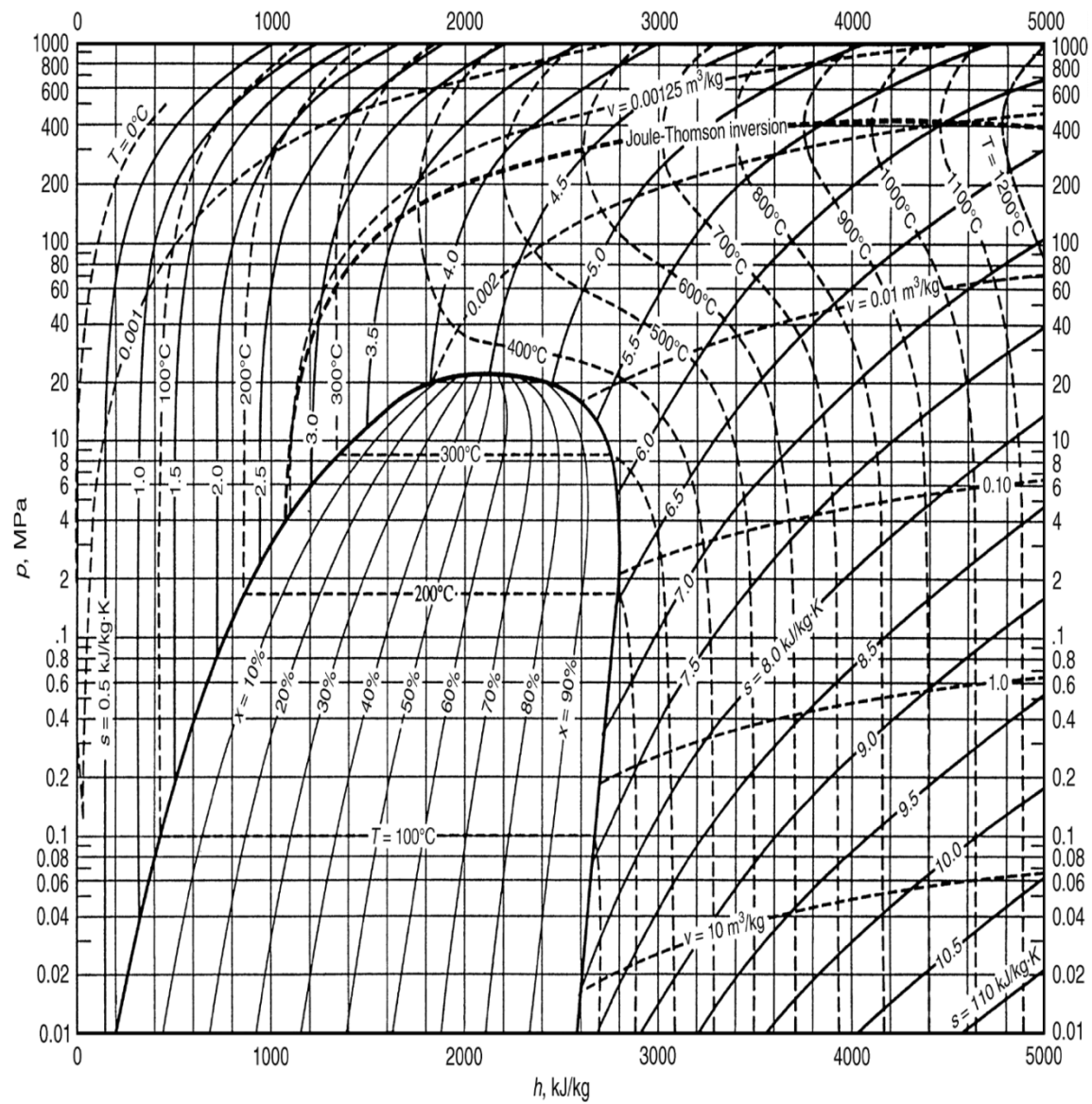


T – h diagram

- Lines of constant pressure originate on the saturated water line.
- The horizontal distance between the saturated water line and the dry saturated steam line represents the amount of latent heat or enthalpy of evaporation, and is called the evaporation line; (enthalpy of evaporation decreases with rising pressure).
- The area to the right of the dry saturated steam line is the superheated steam region, and lines of constant pressure now curve upwards as soon as they cross the dry saturated steam line.

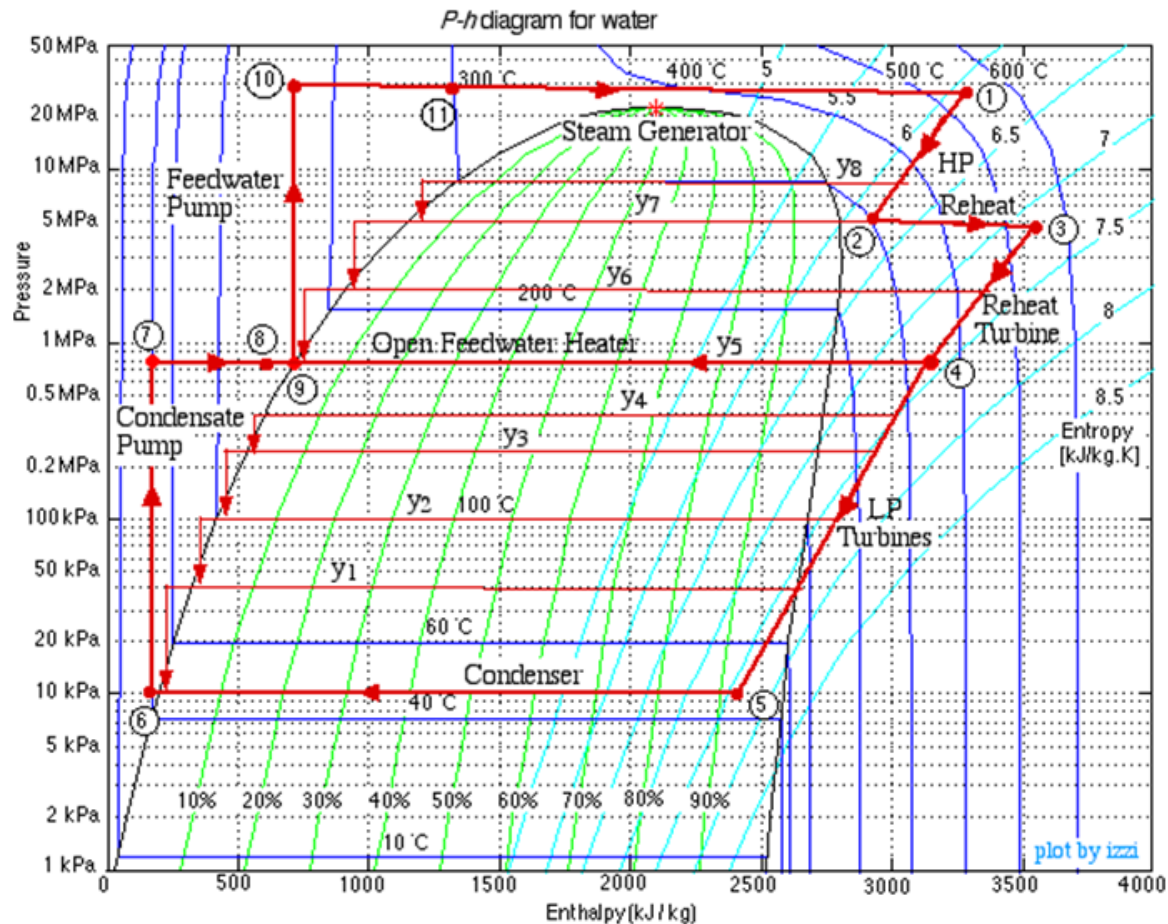
4 / $P - h$ diagram

- **As mentioned above** the common method of describing steam power plant systems is by plotting them on a $T-s$ (temperature-entropy) diagram for steam. This is done exclusively in all thermodynamic text books over many years. This may be cumbersome. We will make exclusive use of $P-h$ (pressure-enthalpy) diagrams to describe the various steam power systems, and it may be of useful practice that problems to be solved should be drawn on the $P-h$ diagram as well.
- A typical $P-h$ diagram for steam is shown below. It should be studied carefully to identify the various parameters lines.



Example

related to future section of the course



Chapter one

Power plant fundamentals

1.05 - How it works

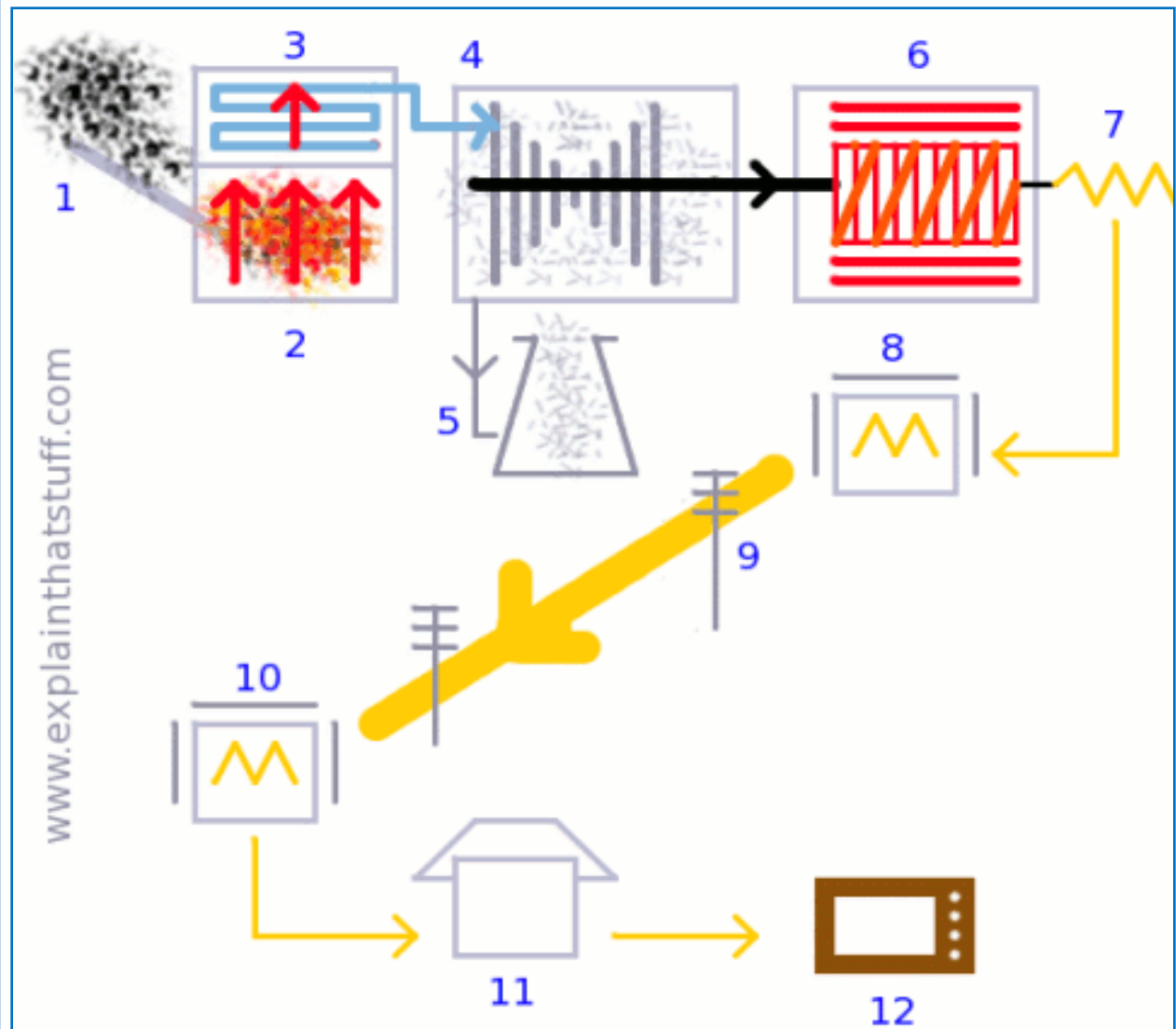
introduction

- When Thomas Alva Edison (1847–1931) constructed one of the first power stations in Pearl Street, New York City, in 1882, he revolutionized the way people used [energy](#).
- Once energy had to be produced where and when it was needed. But a power station separates the producer of energy from the consumer, using [electricity](#) as a go-between.
- This makes it possible to generate electricity in Detroit that will be used in California or to use cheap energy produced at quiet periods during the night to produce electricity for peak periods during the day.
- How do power plants actually work? Let's take a closer look!

How does energy get from a power plant to your home?

- The heart of a power station is a large [generator](#) that extracts energy from a fuel.
- Some power stations burn fossil fuels such as coal, oil, or gas. ([Nuclear power](#) stations produce energy by splitting apart [atoms](#) of heavy materials such as uranium and plutonium.)
- The [heat](#) produced is used to turn water into steam at high pressure.
- This steam turns a windmill-like device called a [turbine](#) connected to an electricity generator.
- Extracting heat from a fuel takes place over a number of stages and some energy is wasted at each stage.

In general, a steam power plant using coal for example as fuel, the coal arrives, by some means of transportation, and stored in the plant's coal yard. Conveyor belts (1) carry the coal from the yard into the plant, pulverizers grind the coal into a fine powder. The powdered coal is injected into the steam generator (2-3) where it is burned at high temperature providing the heat energy needed to generate steam that operate the steam turbine (4).



The turbine is coupled to electric generator (6) where electricity is generated (7). A transformer (8) outside the plant's building step up the voltage so that it can be transmitted efficiently over a long distance (9) to consumers (10,11,12)

The main plant component are

1. **Furnace:** The fuel is burned in a giant furnace to release heat energy.
2. **Boiler:** In the boiler, heat from the furnace flows around pipes full of cold water. The heat boils the water and turns it into steam.
3. **Fuel:** The energy that finds its way into your TV, computer, or toaster starts off as fuel loaded into a power plant. Some power plants run on coal, while others use oil, natural gas, or methane gas from decomposing rubbish.
4. **Turbine:** The steam flows at high-pressure around a wheel that's a bit like a windmill made of tightly packed metal blades. The blades start turning as the steam flows past. Known as a **steam turbine** this device is designed to convert the steam's energy into kinetic energy (movement). For the turbine to work efficiently, heat must enter it at a really high temperature and pressure and leave at as low a temperature and pressure as possible.

5. **Cooling tower:** The giant, jug-shaped cooling towers you see at old power plants make the turbine more efficient. Boiling hot water from the steam turbine is cooled in a **heat exchanger** called a condenser. Then it's sprayed into the giant cooling towers and pumped back for reuse. Most of the water condenses on the walls of the towers and drips back down again. Only a tiny amount of the water used escapes as steam from the towers themselves, but huge amounts of heat and energy are lost.
6. **Generator:** The turbine is linked by an axle to a generator, so the generator spins around with the turbine blades. As it spins, the generator uses the kinetic energy from the turbine to make electricity.
7. **Electricity cables:** The electricity travels out of the generator to a transformer nearby.

8. **Step-up transformer:** Electricity loses some of its energy as it travels down wire cables, but high-voltage electricity loses less energy than low-voltage electricity. So the electricity generated in the plant is stepped-up (boosted) to a very high voltage as it leaves the power plant.
9. **Pylons:** Huge metal towers carry electricity at extremely high voltages, along overhead cables, to wherever it is needed.
10. **Step-down transformer:** Once the electricity reaches its destination, another transformer converts the electricity back to a lower voltage safe for homes to use.
11. **Homes:** Electricity flows into homes through underground cables.
12. **Appliances:** Electricity flows all round your home to outlets on the wall. When you plug in a television or other appliance, it could be making a very indirect connection to a piece of coal hundreds of miles away!

images

Power station [transformers](#)



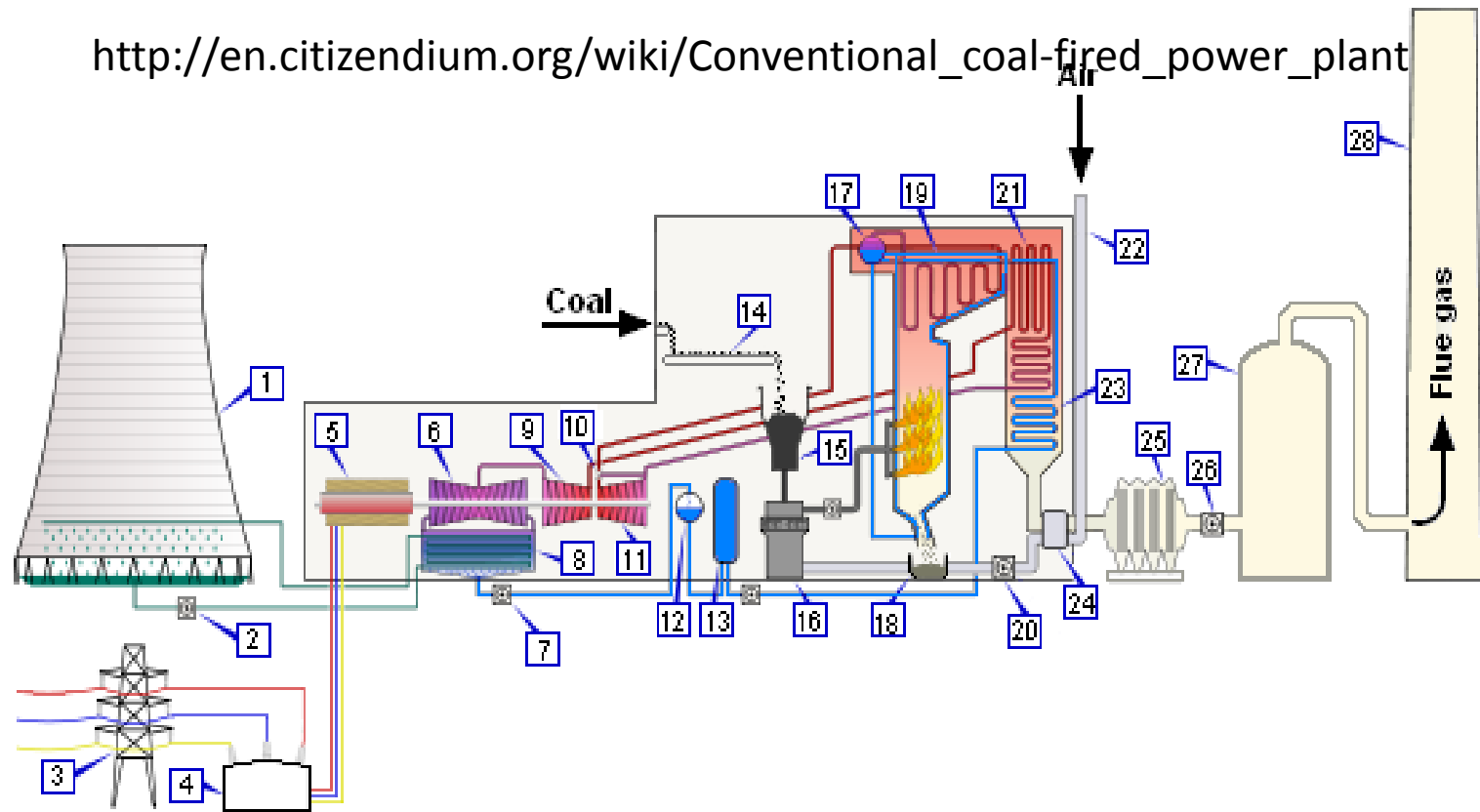
Transmission line



principals

- The principals behind power plant operation are based on a theoretical working cycle known as “Rankine cycle”.
- The **Rankine cycle** is a thermodynamic cycle which converts heat into work. The heat is supplied externally to a closed loop, which usually uses water as the working fluid.
- Thereby, operational plant will look as complicated like the following plant example

http://en.citizendium.org/wiki/Conventional_coal-fired_power_plant



Simplified coal-fired power plant

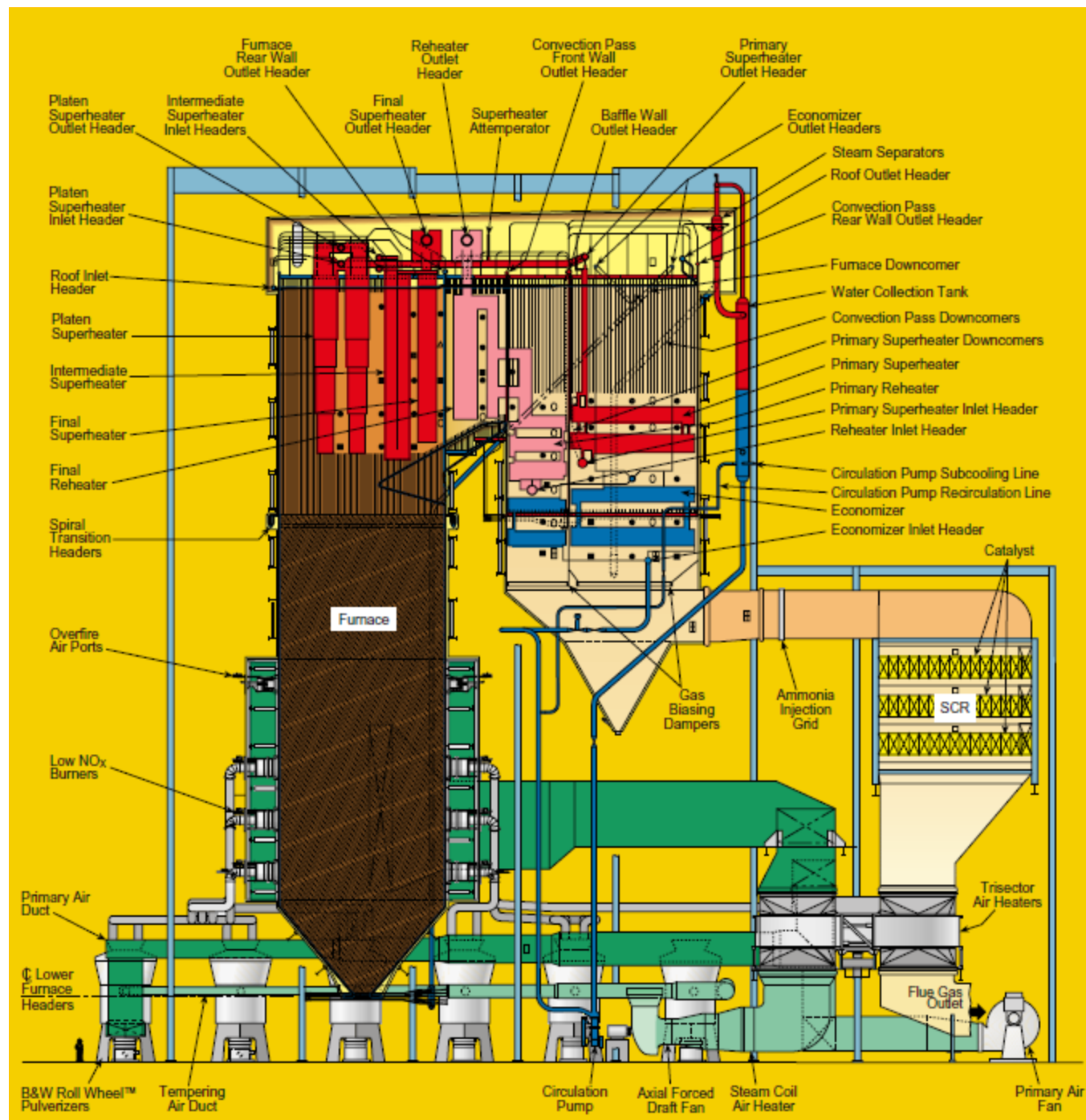
- | | | |
|--------------------------------------|---------------------------------|--------------------------------|
| 1. Cooling tower | 11. High pressure steam turbine | 20. Fan |
| 2. Cooling water pump | 12. Deaerator | 21. Reheater |
| 3. Three-phase transmission line | 13. Feedwater heater | 22. Combustion air intake |
| 4. Step-up transformer | 14. Coal conveyor | 23. Economiser |
| 5. Electrical generator | 15. Coal hopper | 24. Air preheater |
| 6. Low pressure steam turbines | 16. Coal pulverizer | 25. Electrostatic precipitator |
| 7. Boiler feedwater pump | 17. Steam drum | 26. Fan |
| 8. Surface condenser | 18. Bottom ash hopper | 27. Flue gas scrubber |
| 9. Intermediate press. steam turbine | 19. Superheater | 28. Flue gas stack |
| 10. Steam control valve | | |



Two Babcock & Wilcox 420 MW variable pressure, supercritical (spiral wound universal pressure, SWUP™) units with boiler terminal conditions of 248 bar, 596°C.

<http://www.babcock.com/library/brochures-steam.html#E3185>

**Typical B&W spiral
wound universal
pressure boiler.**





Steam Turbine Power Plant

Lignite-fired (brown coal) power plant: this high-output plant began its operation in summer 2000. Its large steam turbine-generator has an output of 906 MW. Designed for supercritical steam conditions of 258 bar at 541 °C it is the first to be equipped with a six-flow low-pressure section.

<http://www.powergeneration.siemens.com/products-solutions-services/power-plant-soln/>



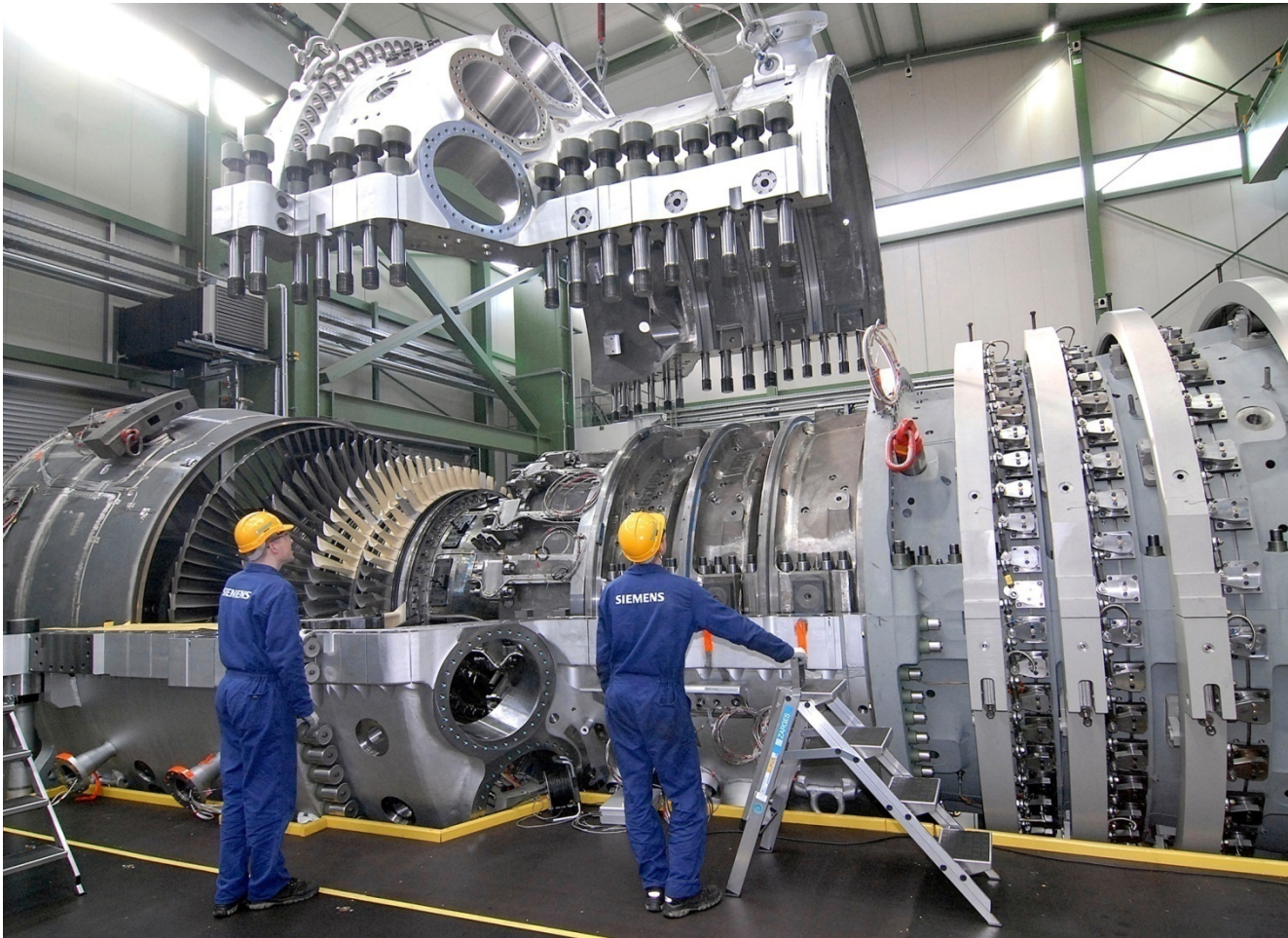
Coal Fired Steam Turbine

Siemens is planning the world's most efficient coal-fired power plant that is expected to operate at a steam temperature of 700°C with an efficiency over 50%. The facility is being designed to produce 40% less CO₂ than the current international. Plans call for the plant to go into service in 2014.



Steam Turbine

Steam turbine (123 MW) for the first commercial solar thermal power plant in the U.S. using a power tower. Steam is generated from water heated by thousands of mirrors. The power plant will begin operations in late 2011, supplying power to 35,000 households. The facility in California's Mojave Desert is being built by BrightSource Energy.



Gas Turbine

The SGT5-8000H gas turbine. Capacity: 340 megawatts (MW). The world's most powerful gas turbine. Output equals that of 13 jumbo jet engines. This unit will be expanded to become a combined cycle power plant with an output of 530 megawatts (MW) with an efficiency greater than 60%. Compared to an average coal-fired power plant with the same output, this power plant emits approx. 2.8 million tons less CO₂ per year (as much as one million automobiles emit).



1.00 - Power plant fundamentals

1.06 – economic & administrative concept

introductory

In all fields of industry, economics plays an important role. In power plant engineering, economics of power system use certain well established techniques for choosing the most suitable system, where the power plant design must be made on the basis of most economical conditions and not on the most efficient conditions., as the profit is the main basis in the design of the plant and its effectiveness is measured financially.

The main purpose of design and operation of the plant is to bring the cost of energy produced to minimum.

Among many factors, the efficiency of the plant is one of the factors that determines the energy cost.



Before concentrating on the economic factors, let's look onto the principles of power plant design consideration:

1. Properly selected location
2. Simplicity of design.
3. Low capital cost
4. Low cost of energy generated
5. High efficiency
6. Low maintenance cost
7. Low operating cost
8. Reliability of supplying power
9. Reserve capacity to meet future power demand



Power plants are obviously built for the purpose of



1 - Generating electricity

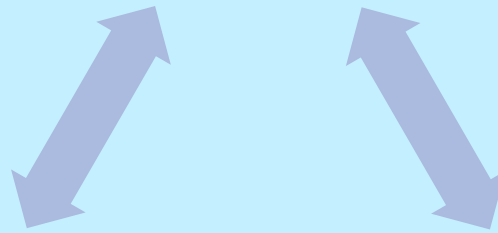


2 - Fulfilling consumer demand for electrical power.



3 - Retaining profitable revenue.

To maintain a balance between
the above three required tasks



Well trained –
experienced –
educated
technical and
administrative
staff

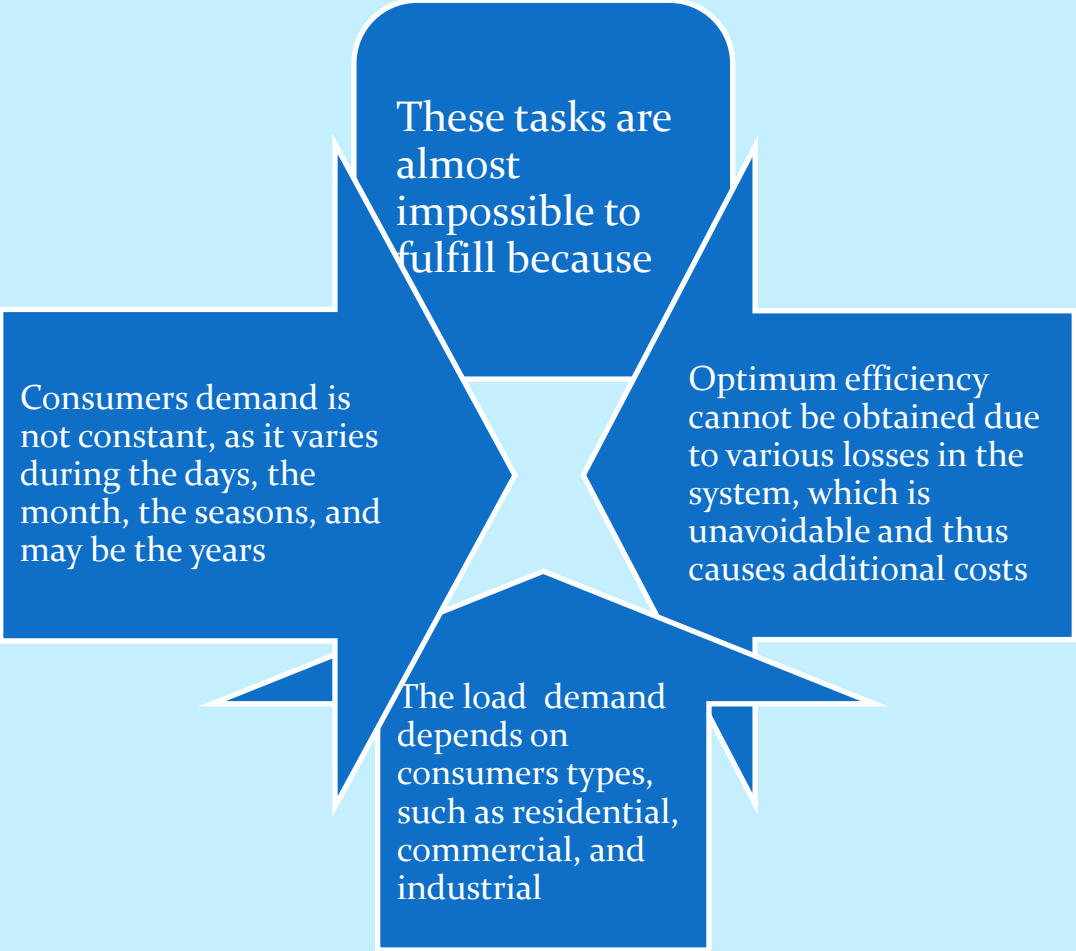
Well
established
modern
technology

Ideally, the generated power is :

That, demanded by the consumers

And , cost the least

At, optimum operating efficiency



These tasks are
almost
impossible to
fulfill because

Consumers demand is
not constant, as it varies
during the days, the
month, the seasons, and
may be the years

Optimum efficiency
cannot be obtained due
to various losses in the
system, which is
unavoidable and thus
causes additional costs

The load demand
depends on
consumers types,
such as residential,
commercial, and
industrial

The above and may be other cases will cause inconsistency of the power plant duties, which makes it a very complicated scheme to run and to operate without any sacrifice, either in cost or efficiency.

Furthermore, knowing all the variables involved makes it even more complicated to administer, as some variables comes suddenly, causing uncontrolled variation in may be consumers demand or plant technical requirements.

Thus, it can be seen how difficult to make a perfect decision in :

Where – when - how

To build a new power plant.

Nevertheless, there are performance factors which provides useful links between various plant contradictories. Such performance factors will be briefed in the next section

Factors related to plant performance & demand variation

1

- Load factor (LF)

2

- Capacity factor (CF)

3

- Utility factor (UF)

4

- Diversity factor (DrF)

5

- Availability factor (AF)

6

- Demand factor (DF)

7

- Plant use factor (PuF)

Terms & definitions

1. Connected load – is the combined continuous rating of all the receiving apparatus on consumers premises which is connected to the system or part of the system under consideration.
2. Demand – is the load expressed in (kW) that is drawn from the source of supply at the receiving terminals averaged over a suitable and specified interval of time.
3. Max demand or peak load – is the greatest of all the demands that have occurred during a given period.
4. Load curve – is a graphic record showing the power demands for every instant during a certain time interval.

1 – load factor

- Load factor is defined as “the ratio of the *average load demanded* to the *peak load demanded* during a certain prescribed period of time”

$$LF = \frac{\text{average load demanded at } \Delta t_x}{\text{peak load demanded at } \Delta t_x}$$

or

$$LF = \frac{\text{energy consumed during } \Delta t_x}{\text{max demand} \times \Delta t_x}$$

- LF is usually less than (1), however, high LF is desirable for :
 1. That the total capacity of the plant is utilized for the max period of time.
 2. High LF means greater average load , which mean that more power units (kWhr) may be generated for a given max demand.
 3. The fixed cost which is proportional to the max demand can be distributed over a greater number of power units (kWhr) supplied.
 4. All of the above will lower cost of electricity being generated and supplied.

2 – capacity factor

- Capacity factor is *defined* as “the ratio of the *actual o/p* of a power plant over a period of time to its *o/p* if it *had operated at full rated capacity* during the same period of time.

$$CF = \frac{\text{actual output during } t_i}{\text{output that could be produced at the rated plant operation during } t_i}$$

- From this definition, it can be seen that ($CF \leq 1$)

- It is also useful to know the annual plant CF, which is expressed as :

$$ACF = \frac{\text{annual kWhr produced}}{\text{plant capacity (kW)} \times \frac{\text{hr}}{\text{year}}}$$

- it is important to note :

CF – applied to power generation system.

LF – applied to power users and consumers

Capacity factor

Capacity factor is the ratio of the actual energy produced in a given period, to the hypothetical maximum possible, i.e. running full time at rated power.

Is capacity factor the same as efficiency?

No, and they are not really related. Efficiency is the ratio of the useful output to the effort input – in this case, the input and the output are energy. The types of efficiency are thermal, mechanical and electrical efficiencies.

These efficiencies account for losses, most of which turn into heat in the atmosphere and water. For instance, the average efficiency of the US electricity generation infrastructure is about 35% – this is because in most thermal plants, about two thirds of the input energy is wasted as heat into the environment. A higher capacity factor is not an indicator of higher efficiency or vice versa.

Is a higher capacity factor “better”?

Yes, within a given technology or a given plant, you can generally say that a higher capacity factor is better and in particular, more economical.

But it does not make sense to compare capacity factors across technologies, because the economics of both production and capacity are so different from one technology to the next – the capacity factor is just one of many factors in judging if a power plant is feasible. Instead, more useful is to compare the cost of producing energy among the various technologies.

examples

Ex.1

(26) Main generators of full rated o/p (700)MW each. (2) auxiliary generators of (50)MW each. The actual o/p for one year was (79.47)Twhr. Find CF.

$$\begin{aligned}\text{CF} &= (\text{actual o/p}) / (\text{max o/p}) \\ &= 79,470,000 / [(26 \times 700) + (2 \times 50)] \times 8760 \\ &= 0.4957\end{aligned}$$

Ex.2

Max o/p (2080) MW, annual generating averaging (4.2)Twhr find (CF)

$$\begin{aligned}\text{CF} &= \text{actual o/p} / \text{max o/p} \\ &= 4,200,000 / 2080 \times 8760 \\ &= 0.23\end{aligned}$$

Reserve capacity

- Reserve capacity (RC) is defined as *“the difference between the total rated capacity of all the units in the grid network and the expected peak demand of the system”*
- *The plant reserve capacity can be approximated as in the following expression:*
- $RC = LF - CF$
- *Where normal values of (RC) usually maintained at about 20%*

3 – utility factor UF

- UF is defined as “*the ratio of maximum demand of a plant to the rated capacity of the plant*”

- Where

$$\text{utility factor} = \frac{\text{max demand of the plant}}{\text{rated capacity of the plant}}$$

- And

$$\text{max demand} = \text{max load} \times \text{LF}$$

- Ex.
- Rated capacity is (200)MW, max load is (100)MW and the LF is (80%), determine the UF

$$\text{utility factor} = \frac{\text{max demand of the plant}}{\text{rated capacity of the plant}}$$

- Since
$$\text{max demand} = \text{max load} \times \text{LF}$$

- Then
- $$\begin{aligned} \text{UF} &= (100 \times 0.80) / 200 \\ &= 0.40 \\ &= 40 \% \end{aligned}$$

4 – diversity factor DrF

- Consider a group of consumers, each individual in the group had a max demand at a certain time.

- The max demand of the group individuals most probably may not occur at one time, but at different instant of time. So :

1. Each individual has his own max demand.
2. Selecting this max demand value of each individual and sum them up to get the total max demand value of the group, and let this be equal to (x)

3. Selecting the highest max demand value among the group individual, and let this be (y)

4. The diversity factor DrF is

$$DrF = \frac{\sum (\text{max demand})_1 + (\text{max demand})_2 + \text{etc}}{\text{highest max demand among the group}}$$

$$DrF = x/y$$

Where (DrF > 1) always

- High DrF is desirable, and it means “low max demand on the plant for a given number of consumers.

5 – availability factor

- It is known as 'the plant operating factor' and it is defined as "the ratio of the time period in which the plant was in operation to the total time period considered."
- This simply means that plant availability is plant available to be used for actual running or as stand-by.
- Stand-by is not really working status, it is nevertheless, available to be used instantly when being required.
- Therefore, total availability time is the sum of the running plus the stand-by time

$$AF = \frac{\text{time period the plant in operation}}{\text{total time intervals}}$$

- i.e

$$AF = \frac{\text{running time}}{\text{time running} + \text{time standby} + \text{stoppage time}}$$

- Ex.1 – a plant is ready to operate during one particular week, but held as standby
- Ex.2 – if plant operates at half rated power for one month

$$AF = 1$$

$$CF = 0$$

$$AF = 1$$

$$CF = 0.5$$

6 – demand factor DF

- The ratio of (a) the maximum real power consumed by a system to (b) the maximum real power that would be consumed if the entire load connected to the system were to be activated at the same time.

$$DF = \frac{\text{max demand of the consumer}}{\text{connected load}}$$

- For a consumer, the demand factor is “the ratio of it’s max demand to the connected load.
- Max demand is the max load (in kW) which a consumer uses at any time.

- Connected load is the total rating (in kW) of the various electrical equipment installed in a consumer’s premises.
- The actual max demand of a consumer is almost always less than his connected load from the grid, as all of his residential appliances may not be in operation at the same time.
- Therefore DF is usually less than (1), but can be equal to (1)
- $DF \leq 1$

7 – plant use factor PuF

PuF is different from CF in that the actual operation power is considered.

Where :

$$\text{annual PuF} = \frac{\text{annual (kWhr) produced}}{\text{plant capacity} \times \text{hrs of plant operation}}$$

1	Load factor	$LF = \frac{\text{average load demanded at } \Delta t_x}{\text{peak load demanded at } \Delta t_x}$
2	Capacity factor	$CF = \frac{\text{actual output during } t_i}{\text{output that could be produced at the rated plant operation during } t_i}$
3	Utility factor	$\text{utility factor} = \frac{\text{max demand of the plant}}{\text{rated capacity of the plant}}$
4	Diversity factor	$DrF = \frac{\sum (\text{max demand})_1 + (\text{max demand})_2 + \text{etc}}{\text{highest max demand among the group}}$
5	Availability factor	$AF = \frac{\text{time period the plant in operation}}{\text{total time intervals}}$
6	Demand factor	$DF = \frac{\text{max demand of the consumer}}{\text{connected load}}$
7	Plant use factor	$\text{annual PuF} = \frac{\text{annual (kWhr) produced}}{\text{plant capacity} \times \text{hrs of plant operation}}$

Load duration curve

- The fundamental difficulty with balancing the 'supply of' and the 'demand for' electricity derives from the physical nature of electricity and the fact that it is currently not commercially viable to store it on a sufficient scale to be of use to electricity utilities.
- in this regard, electricity is a unique commodity in that the rate of it's production must balance the rate at which it is consumed at all time if the electricity system is to maintain stability.

reasons

- Demand for electricity is not constant and fluctuation in load generally occurs :
 1. *Daily variation - At different time of the day to reflect the pattern of working hours and change in people activities ... (lighting; cooking; heating ... etc).*
 2. *Weekly variation - On different days of the week to reflect the pattern of domestic, industrial and commercial activity on weekdays, weekend, and holidays.*
 3. *Season variation - In different months of the year often reflect different climatic conditions, where for example heating and air-conditioning according to the season of the year.*
 4. *Random variation – caused by unexpected factors such as system failure, sudden weather change ... etc*
 5. *Long term growth.*

Load profile

A load profile is a graph of the variation in the electrical load versus time, and it will vary according to

1. customer type (typical examples include residential, commercial and industrial),
2. temperature and holiday seasons.

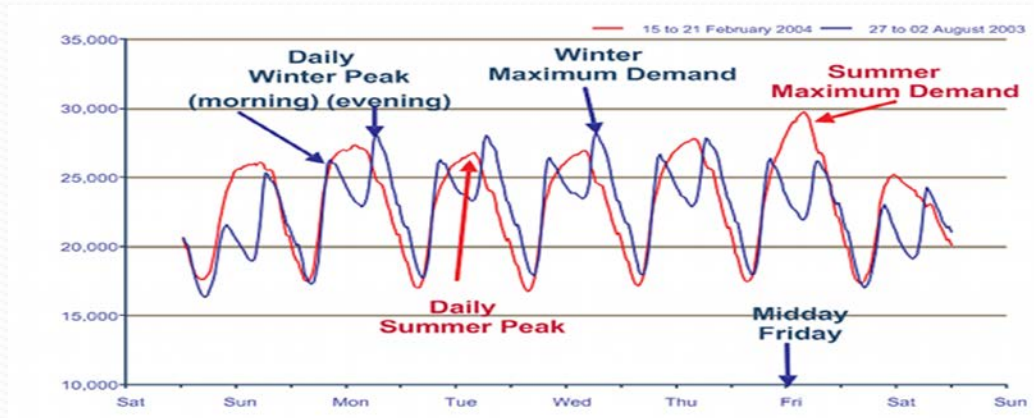
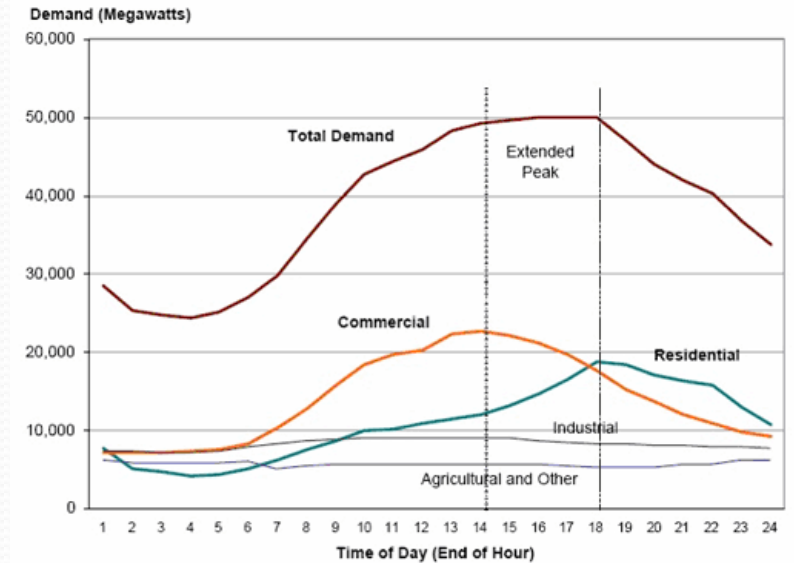
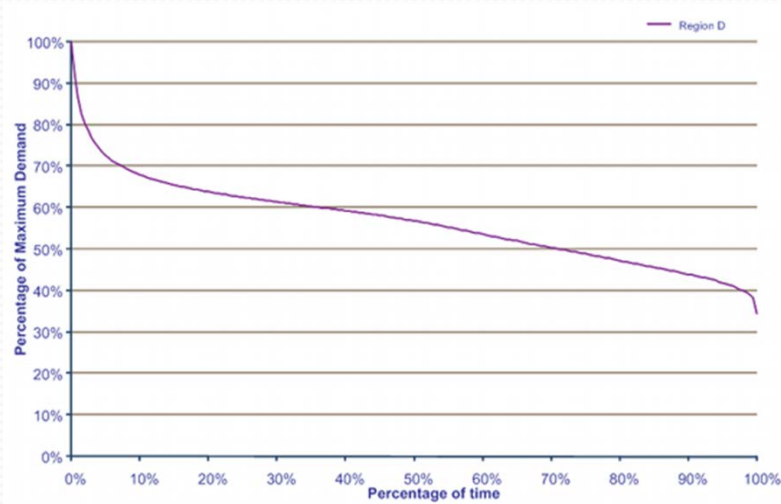
In the electricity generation sector,

I - **load curve** is a chart showing the amount of electricity customers use over a period of time. Generation companies use this information to plan how much power they will need to generate at any given time.

II - **load duration curve** is similar to a load curve. The information is the same but is presented in a different form.

These curves are useful in the selection of **generator** units for supplying electricity.

Due to above ... a load duration curve may be presented in the next diagrams:



Example on demand variation

load demand curve over a period of (24)hrs in summer & winter
i.e, daily and seasonal variation

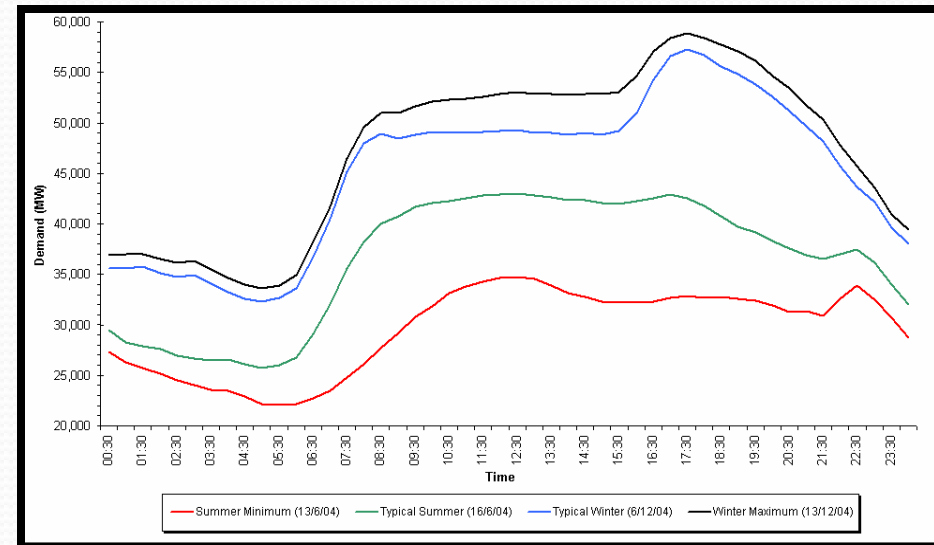
- In summer

peak demand occur in the afternoon where in addition to normal demand an extra high air-conditioning load will be expected.

- In winter

Peak demand occur in the early evening hours, where residential heating will be added to normal load.

- This example is applied to a specific region, city, or country, as geographic location has a marked effects on load variation level.



Electric power generation cost

- This is the cost of new power plant to be constructed, where such costs are divided into three categories :
 1. Capital cost
 2. Operating & maintenance cost
 3. Fuel cost
- These costs are often expressed in unit currency per kWh of power produced.
- Although most reference books use 'mill' (1000mills/\$) as calculation currency, however currency for cost estimation may be in any recognized international or national currency such as (\$, £ , ¥ , ¢ , uoros , dinar ... etc).
- To avoid misunderstanding we shall use "price unit PU" for cost estimation and analysis.
- PU may refer to any of the above mentioned currency.

charging costs

- The cost to the consumer for electric energy charge can be roughly approximated according to :
- Generation – 60%
- Transmission – 10%
- Distribution – 20%
- Administrative/Profit – 10%

As far as our concern as power plant engineering, the generation cost is only considered, because it is directly related to power generating system, therefore knowing such costs can help the engineers to assess the economy of their plant, and therefore works to improve the plant efficiency and performance to maintain good income rate to the investors, and at the same time to maintain and lower the charge cost to consumers.

again , referring to :

1. *Capital cost*
2. *Operating & maintenance cost (O & M)*
3. *Fuel cost*

Can be used for cost estimation whether for new built plant, or the running cost of an existing plant

Electric power produced (EPP)

- To simplify cost estimation, a new term “electric power produced” will be presented which is usually expressed per one year.

- Therefore EPP for one year

$$EPP = P_{rt} \cdot CF \cdot t \quad (\text{kWh})$$

P_{rt} – nominal power plant rating (kW)

CF – plant capacity factor

t - hrs/yr = 8760 hrs/yr

- The EPP is very useful term, as cost of power generation is related to it, and so the overall power generation cost (OPGC) is generally expressed as:

$$OPGC = \frac{\text{capital cost} + O \& M + \text{fuel cost}}{EPP}$$

example

- Ex. – consider a (600)MW plant having
(CF = 35%), find EPP
- solution
- $EPP = P_{rt} \cdot CF \cdot t$
 $= (600\text{MW} \times 1000\text{kW/MW}) (0.35) (8760 \text{ hr/yr})$
 $= 1.84 \times 10^9 \text{ kWh}$

Capital cost

**This is the most difficult to compute due to the large expenditure and time period involved.

However, for simplification, capital cost can be divided into two main categories :

A - initial costs

1. Land
2. Buildings
3. Equipment
4. Installation
5. Overall charges : 'transportation – stores - keeping –interest ...etc'

B - economic charges

1. Interest rate
2. Depreciation : physical → wear & tear – corrosion – aging ...
functional → change of process – technical advancement....
3. Taxes
4. insurance

Fuel cost

- the annual thermal heat required to produce a given amount of electricity can be determined as :

$$E = \dot{m}_f \cdot HHV \cdot \eta_{th}$$

- The annual fuel cost is determined from the amount of fuel used and it's cost per unit of such amount, i.e :

$$\text{fuel cost} = \dot{m}_f \cdot \text{cost}$$

- From above the fuel cost of electricity production can be expressed as :

$$e_f = \frac{\text{fuel cost}}{E} = \frac{\dot{m}_f \cdot \text{cost}}{\dot{m}_f \cdot HHV \cdot \eta_{th}} = \frac{\text{cost}}{HHV \cdot \eta_{th}}$$

- Where

E	– power produced	(kWh/yr)
HHV	– fuel heating value	(kJ/kg)
$\dot{m}_f$	– fuel annual consumption rate	(ton/yr)
η_{th}	– plant thermal efficiency	
cost	– cost of unit mass of fuel	(\$/ton)

O & M cost

- *Labor costs (wages & salaries)*

These will depend on the manning levels and degree of automation of the plant, as well as the living standard .

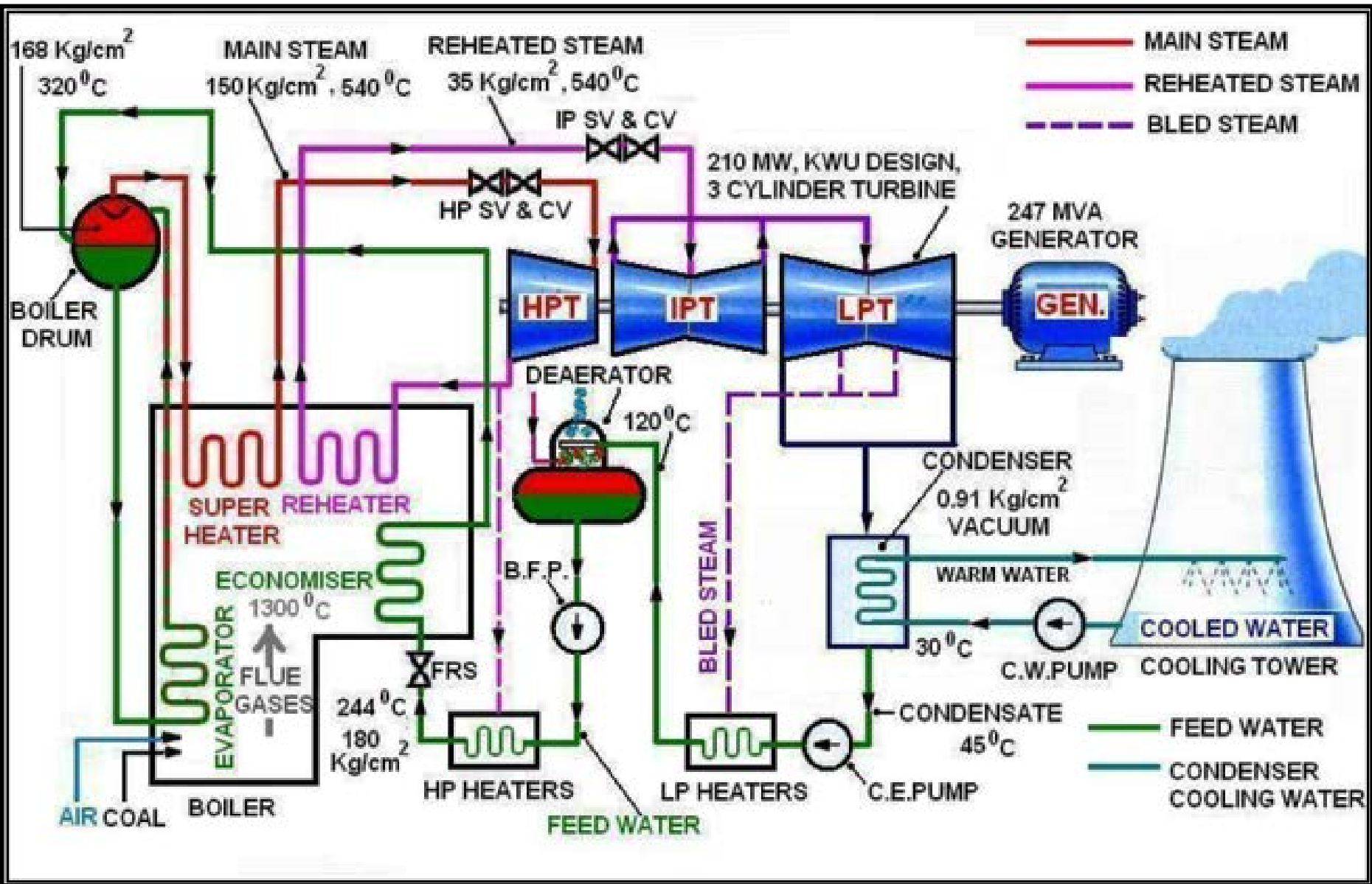
- *Maintenance charges*

Maintenance costs as an average over the plant life (based on previous experience and guidance) should be sought from the manufacturer

Chapter two

steam power plant

2.02.1 – steam cycle
thermodynamics

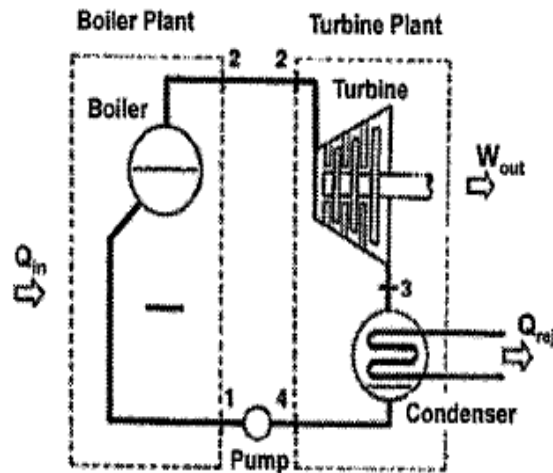


introduction

STEAM BOILER AND TURBINE

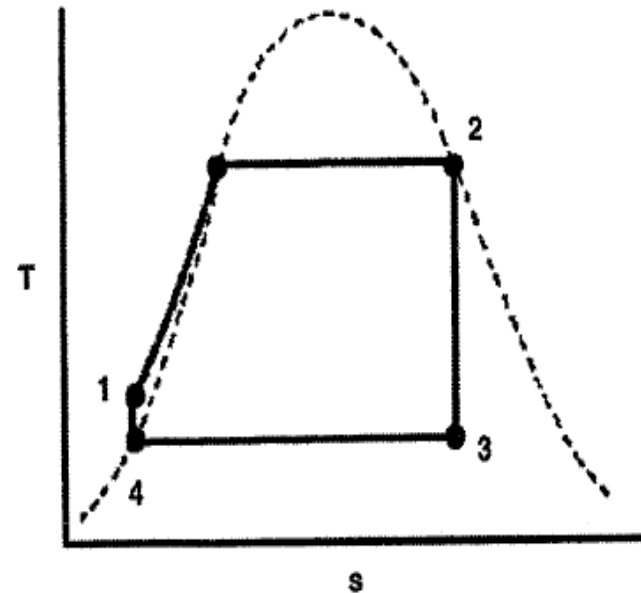
The steam boiler and turbine together make up a steady flow steam cycle using water and steam as the working fluid. Heat is added continuously in a boiler which is effectively a rather complex heat exchanger. Work is produced by a turbine through which steam flows steadily from a high pressure to a low pressure. Heat is rejected in a condenser to establish a net flow of heat from the high temperature reservoir (boiler furnace) to the low temperature reservoir (cooling water). Since the boiler must operate at high pressure to produce high pressure steam, the water is pumped to a high pressure before entering the boiler. Specific thermodynamic processes occur in each component of the system. These four processes together make up the complete thermodynamic cycle.

STEAM BOILER AND TURBINE



<u>Component</u>	<u>Process</u>
Boiler	1 - 2
Turbine	2 - 3
Condenser	3 - 4
Pump	4 - 1

<u>Component</u>	<u>Process</u>
Boiler	1 - 2
Turbine	2 - 3
Condenser	3 - 4
Pump	4 - 1



facts

1. No heat device can generate work without net rejection of heat to a low temperature reservoir.
2. It is impossible for any device that operates in a cycle to receive heat from a single high temperature reservoir and produce a net amount of work and no other effects.

Problems solving strategy

- In solving thermodynamic problems regarding steam power plant process, there is a particular strategy to be followed :
 1. Define one or both “initial & final” conditions
 2. Specify appropriate assumptions.
 3. Derive basic equation.
 4. Sketch system schematic & process chart.
 5. Proceeds to evaluate any unknown variable.

Steam power cycle

Steam power cycles are generally either Carnot or Rankine cycle

The Carnot Cycle is the most efficient thermodynamic cycle that can be obtained when operating between given temperature limits. All the energy is received at a high temperature and all the unavailable energy is rejected at a low temperature. All the available energy is converted into work without loss.

When using a liquid and vapour, such as water and steam, as the working fluid in a thermodynamic cycle the process can be arranged so that heat is transferred to and from the fluid under phase change conditions. In this way the upper temperature of heat acceptance and the lower temperature of heat rejection can be kept constant during the processes of boiling and condensing. This creates the same conditions as dictated by the Carnot Cycle. In a cycle operating on this basis water is boiled to steam at a high temperature and pressure in a boiler and condensed back to water at a low temperature and pressure in a condenser after having done work in the turbine. During expansion in the turbine, initially saturated steam becomes a wet mixture due to the bell shape of the saturation line on a temperature-entropy diagram. It is impractical and inefficient however to compress a wet mixture back to saturated water at the high pressure required to complete a cycle equivalent to the Carnot Cycle. The steam is therefore condensed completely, pumped into the boiler

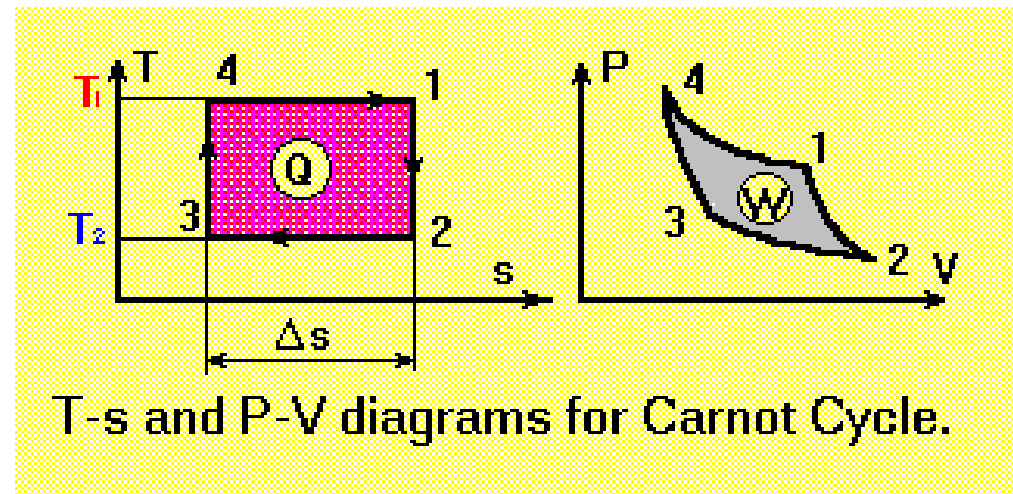
at high pressure and then heated to saturated conditions. Such a cycle is known as a Rankine Cycle.

Carnot cycle

- Carnot cycle is a theoretical operates on the basis of :
 1. All heat supplied is supplied at one fixed temperature.
 2. All heat rejected is rejected at a lower fixed temperature

1 to 2: **Isentropic** expansion
 2 to 3: **Isothermal** heat rejection
 3 to 4: Isentropic compression
 4 to 1: Isothermal heat supply

1. The supplied heat to the cycle per unit mass flow is $Q_1 = T_1 \Delta s$
2. The rejected heat from the cycle per unit mass flow is $Q_2 = T_2 \Delta s$



By applying [the first law of thermodynamics](#) to the [cycle](#), we obtain:

$$Q_1 - Q_2 - W = 0$$

And the thermal efficiency of the cycle will be:

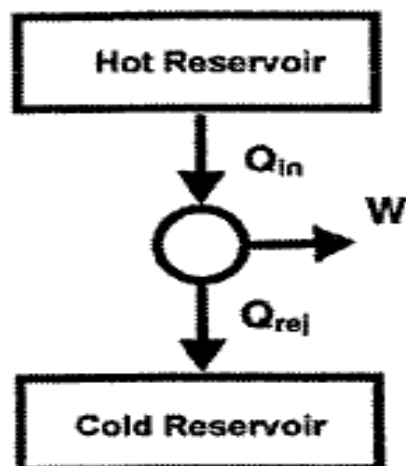
$$\eta = W/Q_1 = 1 - Q_2/Q_1 = 1 - T_2/T_1 = 1 - T_L/T_H$$

Carnot cycle is an ideal heat cycle which is free from all the imperfections of an actual conditions. So, it cannot be realized in actual practice.

Therefore, It is difficult in practice and under real situation to design a system which receives and reject heat at constant temperature. However, a wet vapor is the only working substance that can do it under ideal conditions, where temperature remains constant as the latent heat is supplied or rejected, and the theoretical steam cycle that works on this basis is called “ [Rankine cycle](#) ”

CARNOT CYCLE

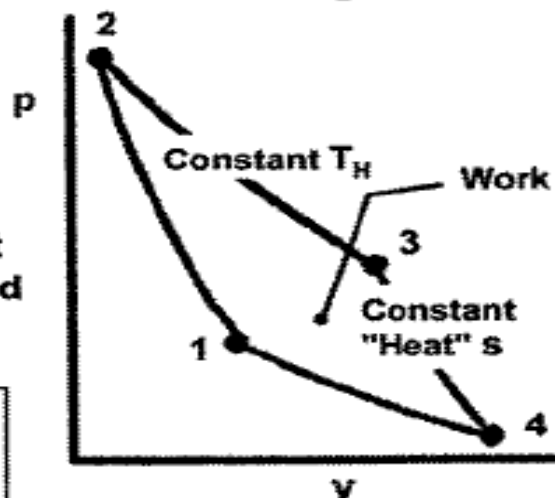
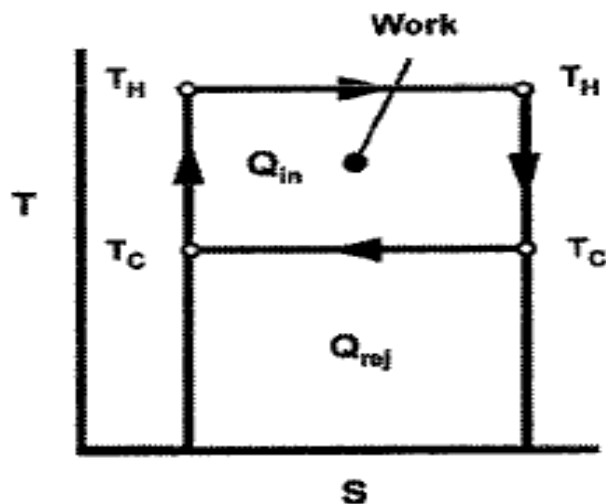
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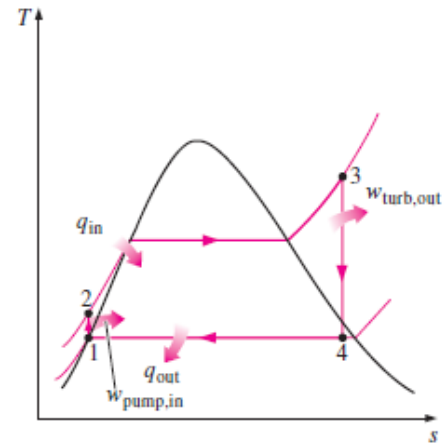
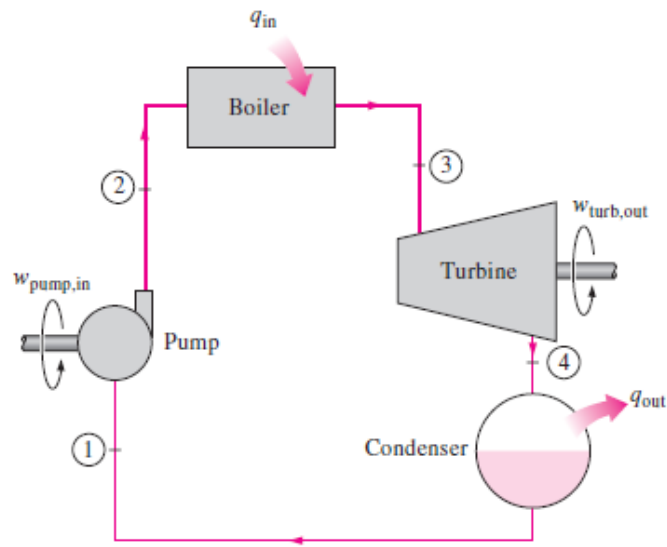
$$\begin{aligned}\eta &= W / Q_{in} \\ &= (Q_{in} - Q_{rej}) / Q_{in} \\ &= 1 - Q_{rej} / Q_{in}\end{aligned}$$

Heat is received at constant temperature. Heat is rejected at constant temperature

$$\eta = \frac{T_H - T_C}{T_H} = 1 - \frac{T_C}{T_H}$$



Rankine cycle



Rankine cycle

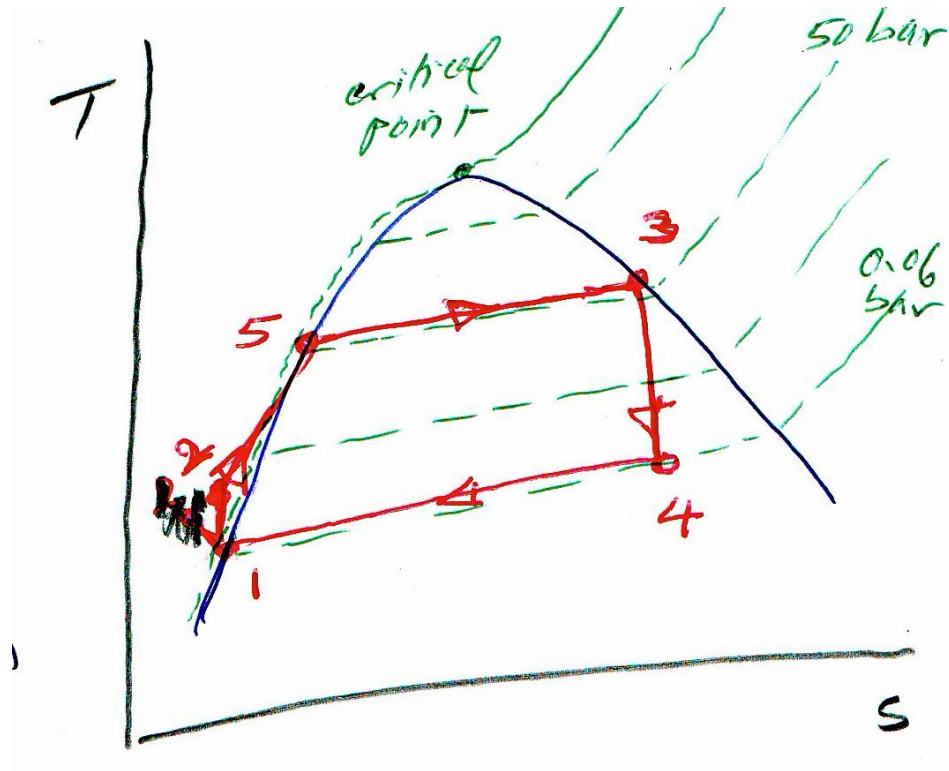
- Since as stated before , it is difficult if not impossible to maintain perfect constant temperature heat addition and heat rejection.
- However, by using water as the working fluid, and considering the latent heat concept can closely resemble the theoretical carnot cycle.
- In practical application, although cannot actually be as efficient, such water-vapor cycle is called “rankine cycle”.
- Rankine cycle is therefore a water-vapor cycle that describe the operation of steam power generation system in it’s thermodynamic aspects.
- Rankine cycle is sometimes referred to as a “practical carnot cycle” due to :
 1. The T-s diagram resembles the carnot cycle.
 2. Heat addition in the boiler and heat rejection in the condenser takes place :
 - i – isothermally in carnot [$\Delta T = 0$]
 - ii - isobarically in rankine [$\Delta P = 0$]
 3. Steam is converted in the condenser to saturated liquid

the deviation of Rankine cycle from that of Carnot as shown in remark(2) above can draw the following conclusions :

1. At the end of condensation the liquid pressure must be raised to boiler pressure by the action of the feed water pump, and this brings about the first kind of power losses.
2. The pumped saturated liquid inside the boiler is out of the liquid saturation line, and therefore heat must be added at constant pressure to return to saturation point, such heat added is another kind of power losses in the cycle.
3. The efficiency of Rankine cycle is limited by the working fluid possible temperature range to avoid construction material failure (T_h & P_h), and on the other side to avoid possible condenser leakage and inability of heat removal (T_L & P_L). Such limits ($T_h = 565^\circ\text{C}$) and ($T_L = 30^\circ\text{C}$) will result in Carnot thermal efficiency of (63%) compared to (42%) in modern coal fired power station.
4. Work required by the pump consumes only (1 to 3 %) of the turbine power o/p, since all vapor is converted to liquid in the condenser. However heat must be added in the boiler to raise pumped liquid to saturation temperature. i.e
pump work is improved $\rightarrow\rightarrow\rightarrow$ thermal eff. Is increased
overall heat added $\rightarrow\rightarrow\rightarrow$ thermal eff. Is reduced
therefore, the resultant effects $\rightarrow$ is better thermal eff.

example

- This is an example of a typical Rankine cycle operating between pressures (50 bars) and (0.06 bar).
- The various cycle processes are described as follows :



$3^- \rightarrow 4^-$: the working fluid is pumped from low to high pressure, as the fluid at this stage is in the liquid state, and thus requires little input energy.

$4^- \rightarrow 1$: the high pressure liquid enters the boiler where it is heated at constant pressure by external heat source to become dry saturated vapor.

$1 \rightarrow 2$: the dry saturated vapor expands through the turbine and thus generates power. This will decrease temperature and pressure of the vapor, causing possible degree of condensation.

$2 \rightarrow 3^-$: the wet vapor enters a condenser where it condenses at constant pressure to saturated liquid.

Ideally, the above processes are :

i – isentropic compression ($3^- \rightarrow 4^-$), and isentropic expansion ($1 \rightarrow 2$), and so no change in entropy, where the process lines are vertical.

ii – most commonly, the vapor at the end of expansion is prevented away from superheated region, thus reducing the condenser heat load.

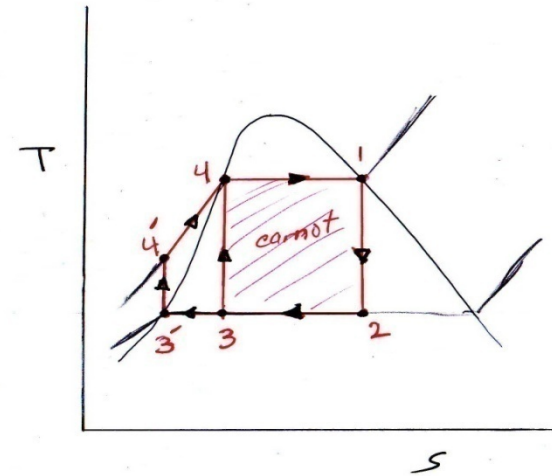
From this diagram :

$$Q_{in} = h_1 - h_{4^-} \quad \text{and} \quad Q_{out} = h_2 - h_{3^-}$$

$$W_{pump} = h_{4^-} - h_{3^-} = v(P_2 - P_1) / \eta_{pump, is}$$

$$W_{turb} = h_1 - h_2$$

$$\eta_{th} = W_{turb} / Q_{in}$$



** Ideally in Carnot cycle, state points (2&3) are at the unsaturated temperature in case of both liquid and vapor.

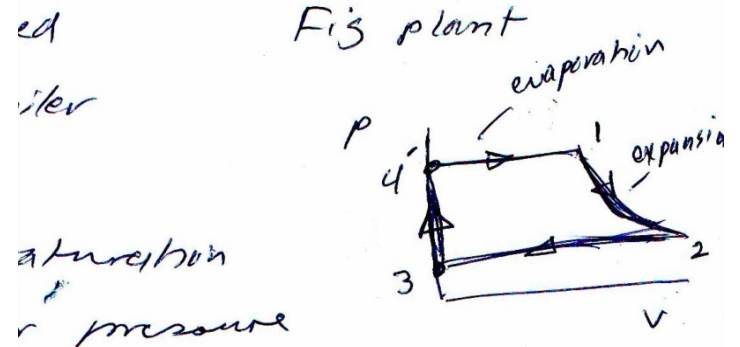
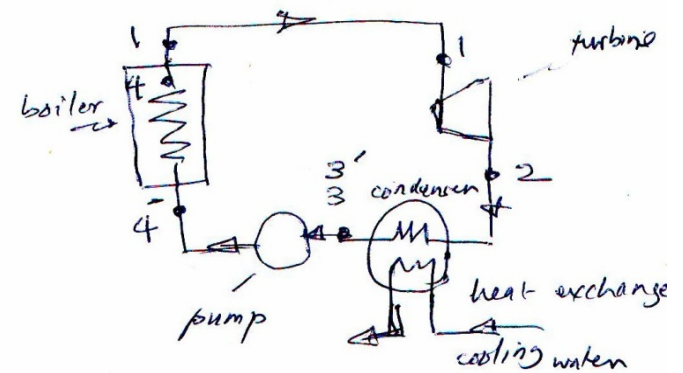
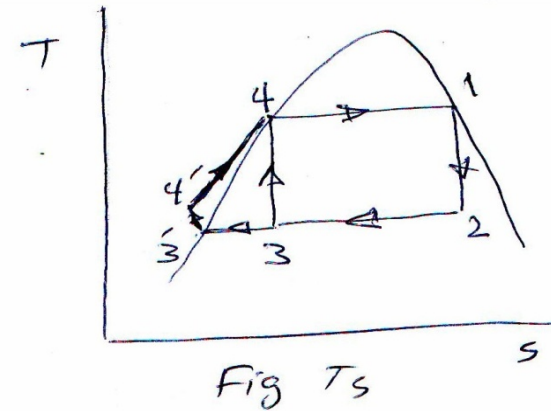
** State point (3) in particular consists of a mixture of vapor and water (wet steam) which is complicated to be pumped.

** If condensation proceeds to completion at (3'), where it is returned to water, and so, water will be easier to pump up to boiler pressure (4').

** But point (4') is not at saturation (T) corresponding to boiler pressure, thus heat must be supplied to change water from (T4') to saturated water at (T4) at constant pressure but not at constant temperature.

** This is a brief description of what will be known as '**Rankine cycle**'

** In actual practice, the state point (1) inlet to turbine may well be [wet steam, saturated steam, or superheated steam] depending on the operating requirement, whereby point (1) moves accordingly on the T-s diagram.



Rankine cycle thermodynamics

- Steady flow energy analysis
 1. heat addition inside the boiler $W = 0$
 2. expansion process in the turbine is adiabatic and isentropic
 $Q = 0$ and $\Delta s = 0$
 3. heat rejection inside the condenser $W = 0$
 4. compression in pump is also adiabatic and isentropic $Q = 0$ and $\Delta s = 0$

$$h_x + Q = h_y + W$$

where x & y refer to initial & final state point of the process

i – boiler $4^- \rightarrow 1$ $h_{4^-} + Q_{4^-1} = h_1 + W \quad [w = 0]$

$$Q_{4^-1} = h_1 - h_{4^-}$$

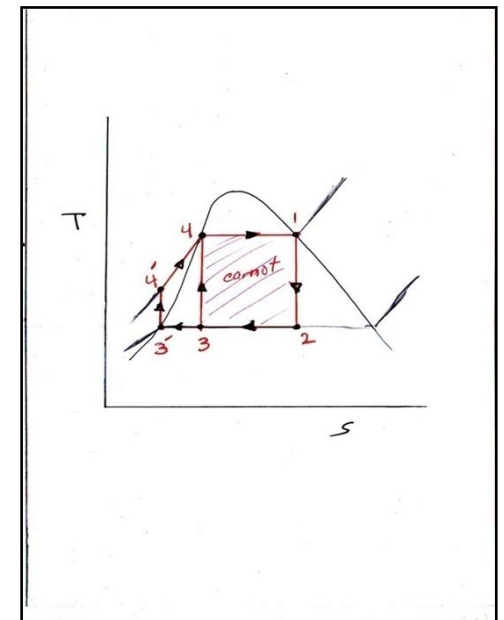
ii – turbine $1 \rightarrow 2$ $h_1 + Q_{12} = h_2 + W_{12}$

expansion is

[adiabatic $Q = 0$] and

[isentropic $s_1 = s_2$]

therefore $W_{12} = h_1 - h_2$



$$\text{iii} - \text{condenser } 2 \rightarrow 3^- \quad h_2 + Q_{23^-} = h_{3^-} + W$$

$$W = 0 \quad Q_{23^-} = h_2 - h_{3^-}$$

$$\text{iv} - \text{pump } 3^- \rightarrow 4^- \quad h_{3^-} + Q_{3^-4^-} = h_{4^-} + W_{3^-4^-}$$

compression is adiabatic & isentropic

$$W_{3^-4^-} = h_{3^-} - h_{4^-} \quad \text{this (-ve) work}$$

$$W_{3^-4^-} = h_{3^-} - h_{4^-} \quad \text{which is the actual work input to pump}$$

also work input to pump can be expressed in terms of specific volume and pressure drop i.e

$$W_{3^-4^-} = v (P_{4^-} - P_{3^-})$$

$$h_{3^-} - h_{4^-} = v (P_{4^-} - P_{3^-})$$

From these analysis we can summarize the results as follows :

W &Q	boiler	turbine	condenser	pump
W	0	$h_1 - h_2$	0	$h_4^- - h_3^-$
Q	$h_1 - h_4^-$	0	$h_2 - h_3^-$	0

However, the useful work output from the power plant system is that amount actually used to run the electrical generator, and this is called 'net work'

Net work = work produced by turbine
 – work consumed by pump

$$W_{\text{net}} = (h_1 - h_2) - (h_4 - h_3)$$

The work consumed by the pump is very small and ranges only to (1-3) % of the turbine power, so it is almost always neglected in general plant performance evaluation, therefore

$$W_{\text{net}} = (h_1 - h_2)$$

this would be fairly acceptable

the heat supplied to the boiler is well defined quantity, which is as stated before is

$$Q_b = h_1 - h_4$$

From the two expressions (W_{net} & Q_b)

$$Q_b = h_1 - h_4$$

$$W_{net} = h_1 - h_2$$

the plant thermal efficiency is evaluated according to Rankine cycle as follows :

$$\eta_R = \frac{\text{net work output}}{\text{heat supplied to boiler}}$$

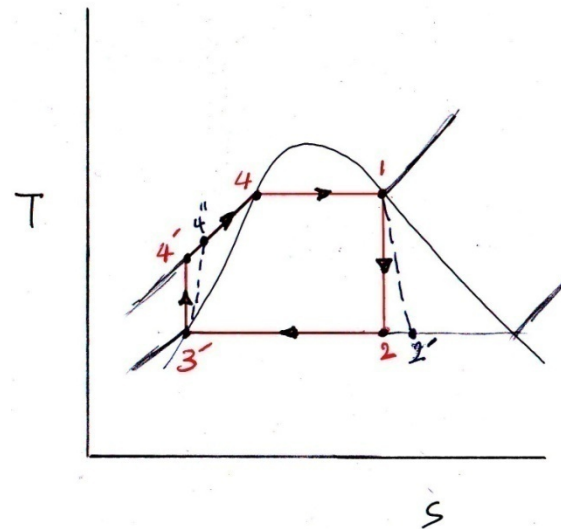
$$\eta_R = \frac{h_1 - h_2}{h_1 - h_4}$$

this is considered as theoretical efficiency, which is not exactly obtainable in practice due to various losses encountered in actual operation.

Although the theoretical best efficiency for any cycle is the Carnot cycle efficiency, the Rankine cycle though, provides a more practical ideal cycle for the comparison of steam power cycle with similar cycles.

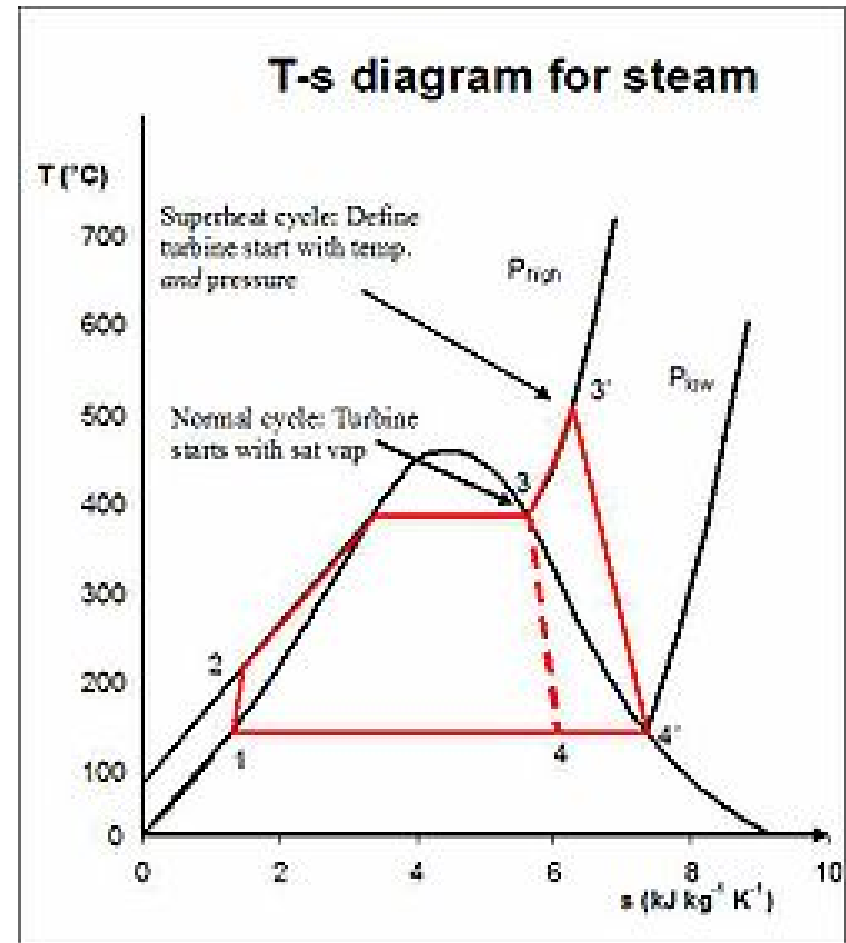
Actual plant efficiency

- Under actual operating conditions, the plant efficiency is the actual efficiency, which is a function of actual work.
- Actual work is through expansion process ($1 \rightarrow 2'$) while isentropic expansion process is ($1 \rightarrow 2$).
- Details of this topic will be discussed in later sections.



Non - ideal

- In a real Rankine cycle, the compression by the [pump](#) and the expansion in the [turbine](#) are not isentropic. In other words, these processes are non-reversible and [entropy](#) is increased during the two processes. This somewhat increases the [power](#) required by the pump and decreases the power generated by the turbine.



Isentropic & actual efficiency

1. Ideal cycle $\rightarrow\rightarrow$ *processes of expansion in turbine and compression in pump are isentropic, i.e reversible & adiabatic*
2. actual cycle $\rightarrow\rightarrow$ *expansion & compression are irreversible processes*

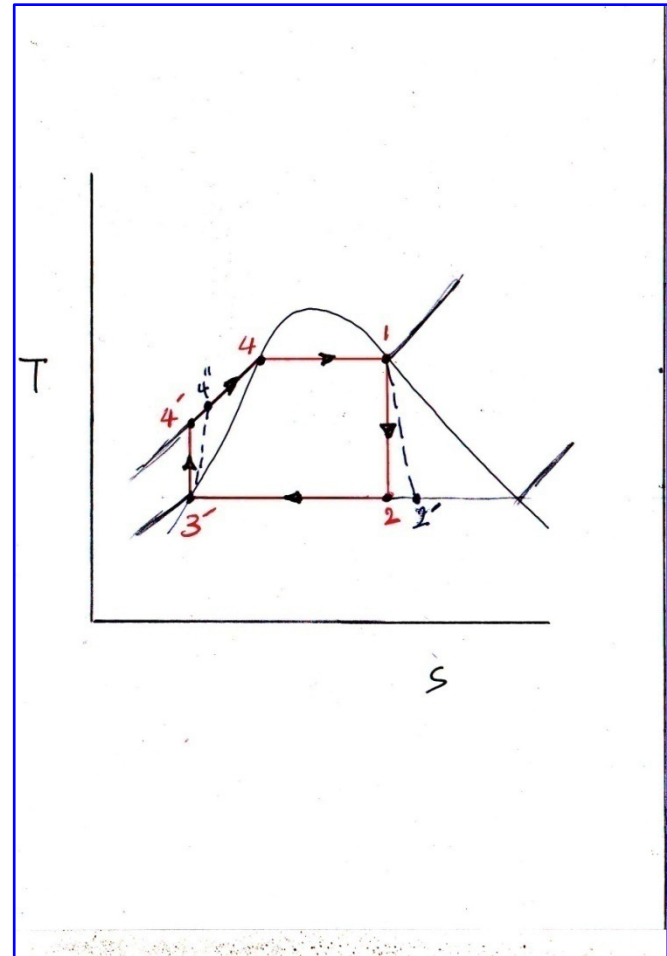
Therefore :

$$\eta_{is.exp} = \frac{\text{actual work o/p}}{\text{isentropic work o/p}}$$

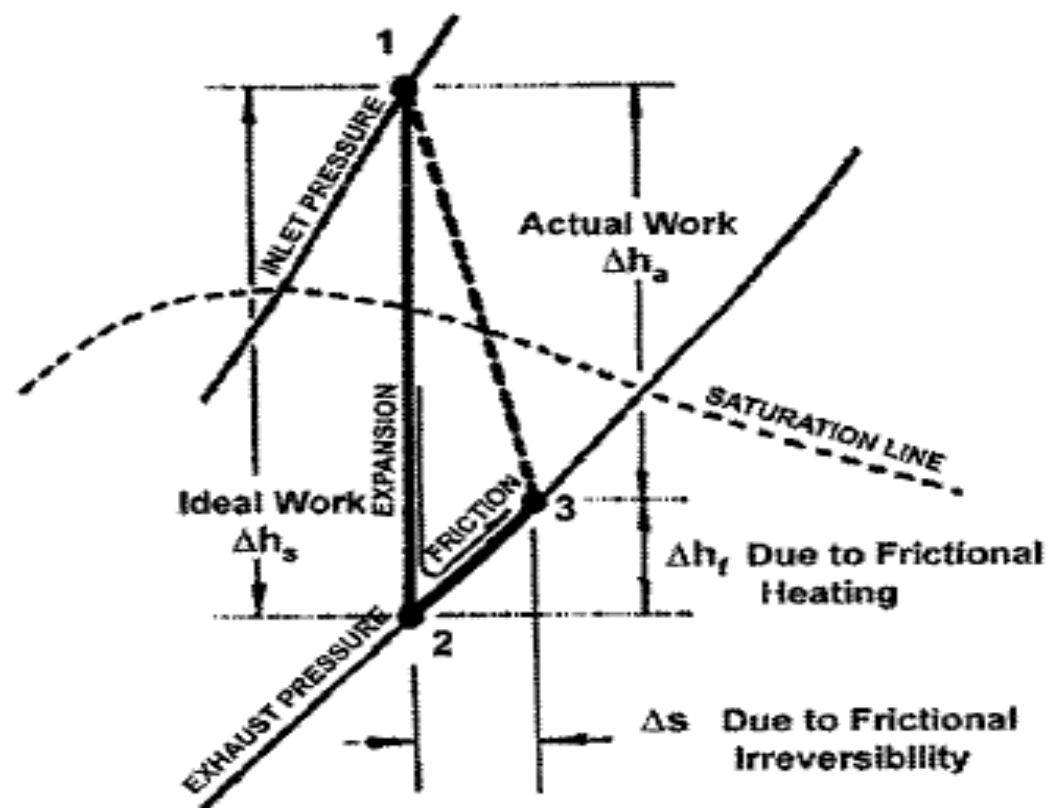
$$\eta_{is.comp} = \frac{\text{isentropic work i/p}}{\text{actual work i/p}}$$

Turbine isentropic eff.

$$\eta_{is.tur} = \frac{W_{12^-}}{W_{12}} = \frac{h_1 - h_{2^-}}{h_1 - h_2}$$



TURBINE INTERNAL EFFICIENCY



Internal Efficiency:

$$\eta = \frac{\text{Actual Work}}{\text{Ideal Work}} = \frac{\Delta h_a}{\Delta h_s}$$

$$\eta = \frac{h_1 - h_3}{h_1 - h_2}$$

Relative efficiency efficiency ratio

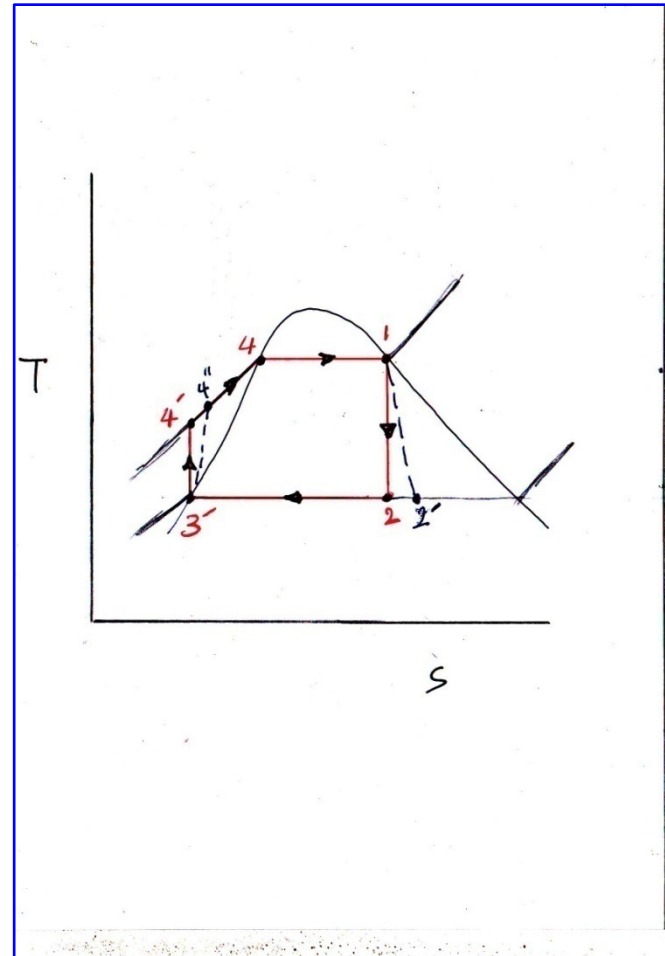
- The efficiency of steam power plant is determined by the use of rankine cycle & relative efficiency.
- Relative eff. is also known as efficiency ratio.

$$\text{relative eff.} = \frac{\text{actual plant thermal eff.}}{\text{rankine cycle thermal eff.}}$$

$$\eta_{rel} = \frac{\eta_{act}}{\eta_R}$$

$$\eta_{act} = \frac{h_1 - h_2}{h_1 - h_{4''}}$$

$$\eta_R = \frac{h_1 - h_2}{h_1 - h_{4'}}$$



$$\eta_{rel} = \frac{\eta_{act}}{\eta_R} \rightarrow \eta_{act} = \frac{h_1 - h_{2^-}}{h_1 - h_{4''}} \quad \text{and} \quad \eta_R = \frac{h_1 - h_2}{h_1 - h_{4^-}}$$

$$\eta_{rel} = \frac{h_1 - h_{2^-} / h_1 - h_{4''}}{h_1 - h_2 / h_1 - h_{4^-}}$$

but ($h_{4^-} \approx h_{4''}$)

$$\eta_{rel} = \frac{h_1 - h_{2^-}}{h_1 - h_2}$$

This is actually the turbine isentropic efficiency as shown previously.

Performance criteria

1. Work ratio
2. Relative cycle eff.
3. Specific steam consumption
4. Condenser heat load
5. Power output

1. Work ratio

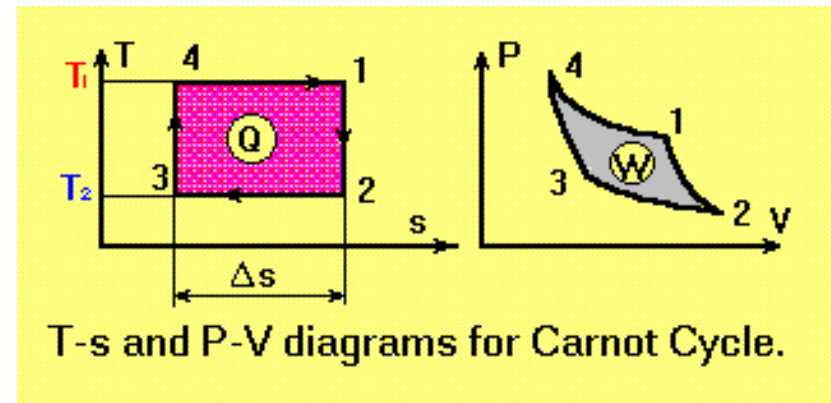
This is better understood by using carnot cycle,
where work done is equal to area under the
PV diagram

Net work of the cycle = area 12341

Gross expansion work = area 412AB4

Work of compression = area 23BA2

Net work = expansion area – compression area



$$\text{work ratio} = \frac{\text{net work output}}{\text{gross work input}}$$

$$WR = \frac{\text{area 12341}}{\text{area 412AB4}}$$

2. Relative efficiency efficiency ratio

- As shown previously, this is the ratio of [actual / ideal] efficiencies, where the ideal efficiency is meant rankine cycle eff.

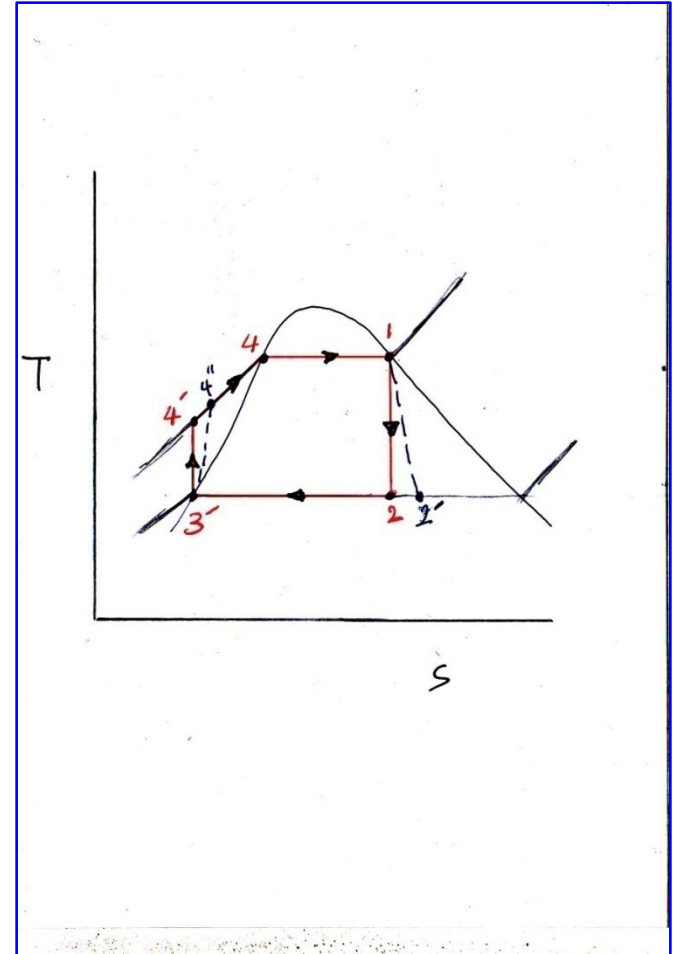
$$\text{relative eff.} = \frac{\text{actual plant thermal eff.}}{\text{rankine cycle thermal eff.}}$$

$$\eta_{rel} = \frac{\eta_{act}}{\eta_R}$$

$$\eta_{act} = \frac{h_1 - h_2}{h_1 - h_{4''}}$$

$$\eta_R = \frac{h_1 - h_2}{h_1 - h_{4'}}$$

$$\eta_{rel} = \frac{h_1 - h_2}{h_1 - h_2}$$



This is the turbine isentropic efficiency

3. Specific steam consumption

This is a very useful performance parameter of a steam power plant, where it is simply defined as “*the mass rate of steam in kg/hr to produce 1kW of power.*” and can be expressed by :

$$SSC = \frac{3600}{h_1 - h_2} \quad \text{kg/kw.hr}$$

4. Condenser heat load

For comparing different plants, the condenser heat removal rate is used, where

$h_2 - h_{3^-}$ = heat removed by cooling water per kg of steam

The rate of heat removal in condenser per unit power output is :

$$Q_{cond} = SSC (h_2 - h_{3^-})$$

$$kJ/kW.hr = \left(kg/kW.hr \right) \left(kJ/kg \right)$$

*low values of Q_{cond} is better, which means that more power is utilized and less rejected
on the contrary, high value of Q_{cond} is undesirable, as this means that more heat is lost*

5. Power output

The power output is defined as the rate of doing work, and work is the enthalpy drop across the turbine.

$$\text{Work} = \Delta h$$

$$\dot{m} = \text{kg/s mass rate}$$

And so the power can be evaluated as :

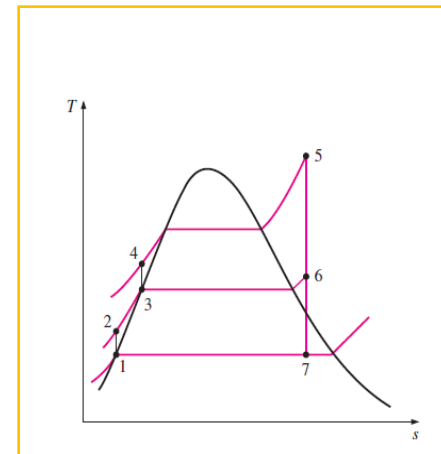
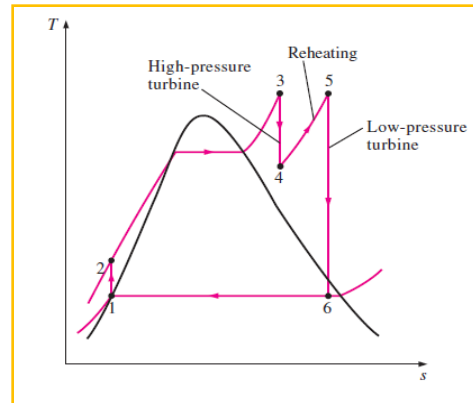
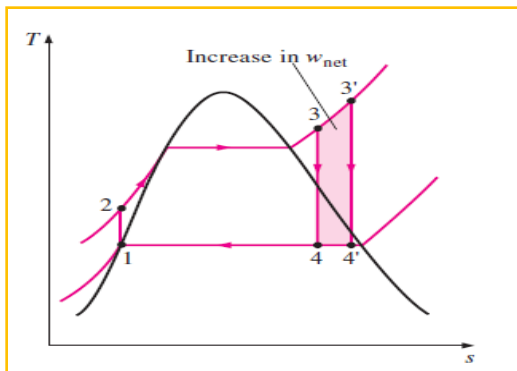
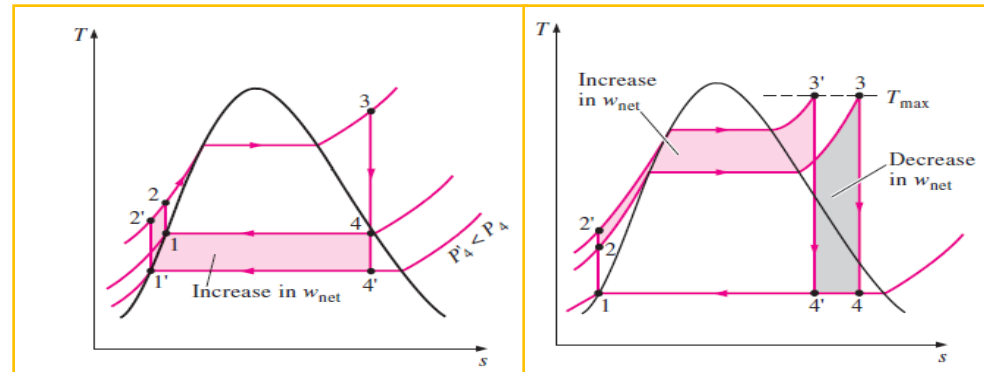
$$\text{Power} = \dot{m} \cdot \Delta h$$

$$= (\text{kg/s}) (\text{kJ/kg})$$

$$= \text{kJ/s}$$

$$= \text{kW}$$

- The efficiency of the steam turbine will be limited by water droplet formation. As water condenses, water droplets hit the turbine blades at high speed, causing “pitting & erosion”, and so, gradually decreasing the life and efficiency of the turbine.
- In order to avoid above disadvantages and improve cycle efficiency, the followings are to be used wherever possible :
 - i – lowering the Condenser Pressure
 - ii – Increasing the Boiler Pressure
 - iii – cycle with superheat
 - iv – cycle with reheat
 - v – cycle with regeneration



Boiler heating arrangement

- normal steam generation, superheating and preheating, are all heating processes inside the boiler.
- General these systems are arranged in three banks of tubes :
 1. 1st bank $\Rightarrow$ heating to dry saturated steam.
 2. 2nd bank $\Rightarrow$ heating to superheat steam.
 3. 3rd bank $\Rightarrow$ reheating of the extracted steam

Boiler heating arrangement

- Normal steam generation, superheating and preheating, are all heating processes done inside the boiler.
- Generally these systems are arranged in three banks of tubes :

1st bank ⇒

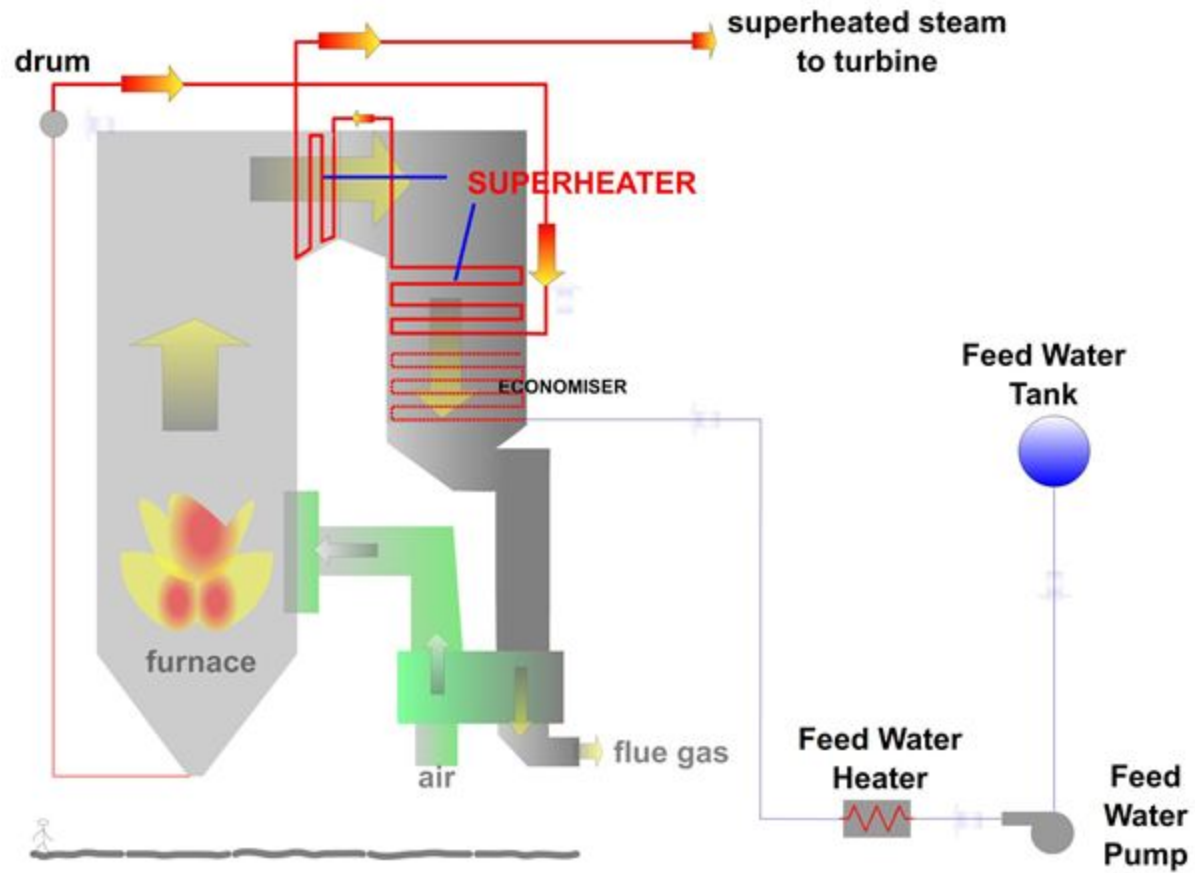
- heating to dry saturated steam

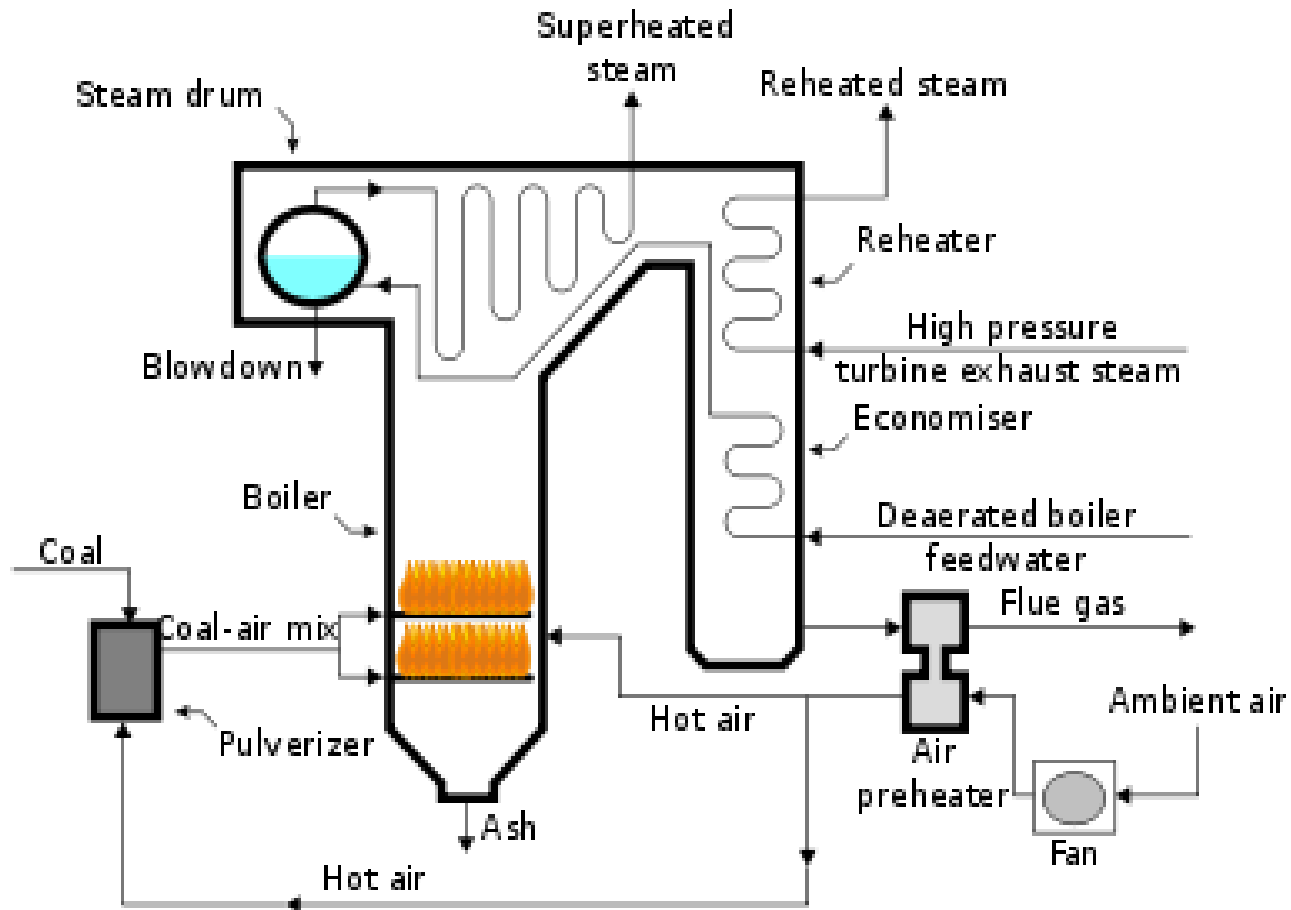
2nd bank ⇒

- heating to superheat steam

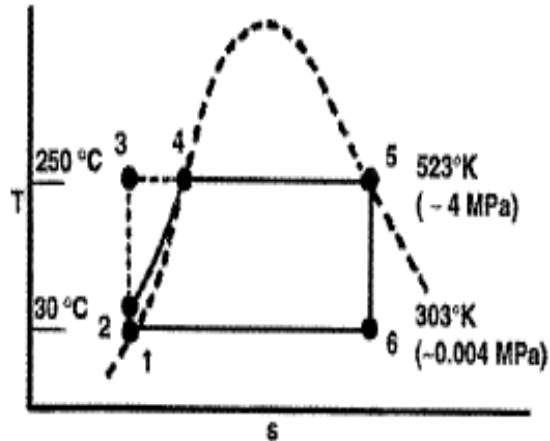
3rd bank ⇒

- reheating of the extracted steam





CARNOT & RANKINE CYCLE



Carnot Cycle 1-3-5-6

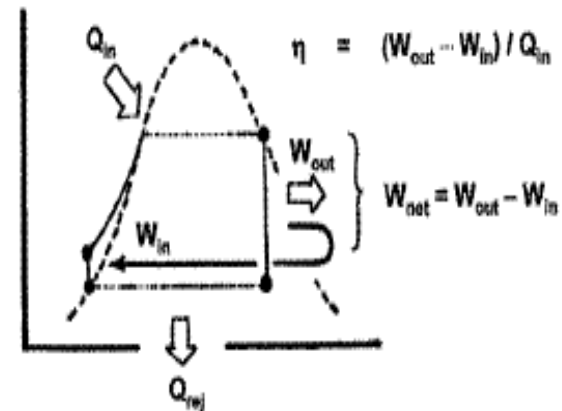
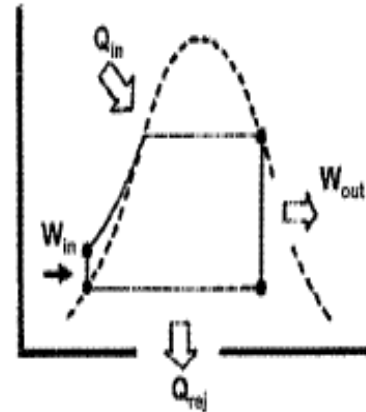
$$\eta = \frac{T_H - T_C}{T_H} = \frac{523 - 303}{523} = \frac{220}{523} = 0.42 = 42\%$$

Rankine Cycle 1-2-4-5-6

h_1	=	126	kJ/kg
h_2	=	130	kJ/kg
h_4	=	1085	kJ/kg
h_5	=	2802	kJ/kg
h_6	=	1835	kJ/kg

$$\eta = \frac{h_5 - h_6}{h_5 - h_2} = \frac{2802 - 1835}{2802 - 130} = \frac{976}{2676} = 0.36 = 36\%$$

EFFICIENCY DEFINITION



$$\eta = (W_{out} - W_{in}) / Q_{in}$$

$$W_{net} = W_{out} - W_{in}$$

Solved Examples on Reversible Heat Engine

Solved Examples

1. A Carnot engine operates between 227°C and 127°C .If it absorbs 60×10^4 calorie at high temperature, how much work per cycle can the engine perform?

Solution

$$T_1 = 273 + 227 = 500\text{K}$$

$$T_2 = 273 + 127 = 400\text{K}$$

$$\eta = 1 - (T_2/T_1) = 1 - (400/500) = 1/5$$

$$\text{But } \eta = W/Q_1$$

Or

$$W = \eta Q_1 = 1/5 \times 60 \times 10^4 = \mathbf{12 \times 10^4 \text{ cal} = 50.4 \times 10^4 \text{ J}}$$

2. A Carnot engine absorbs 100J of heat from a reservoir at 127°C and rejects 600J of heat during the cycle. Calculate (i) the efficiency of the engine (ii) the temperature of the sink and (iii) the amount of useful work done during each cycle?

Solution

$$\text{Heat absorbed from hot reservoir, } Q_1 = 1000\text{J}$$

$$\text{Heat rejected to the sink, } Q_2 = 600\text{J}$$

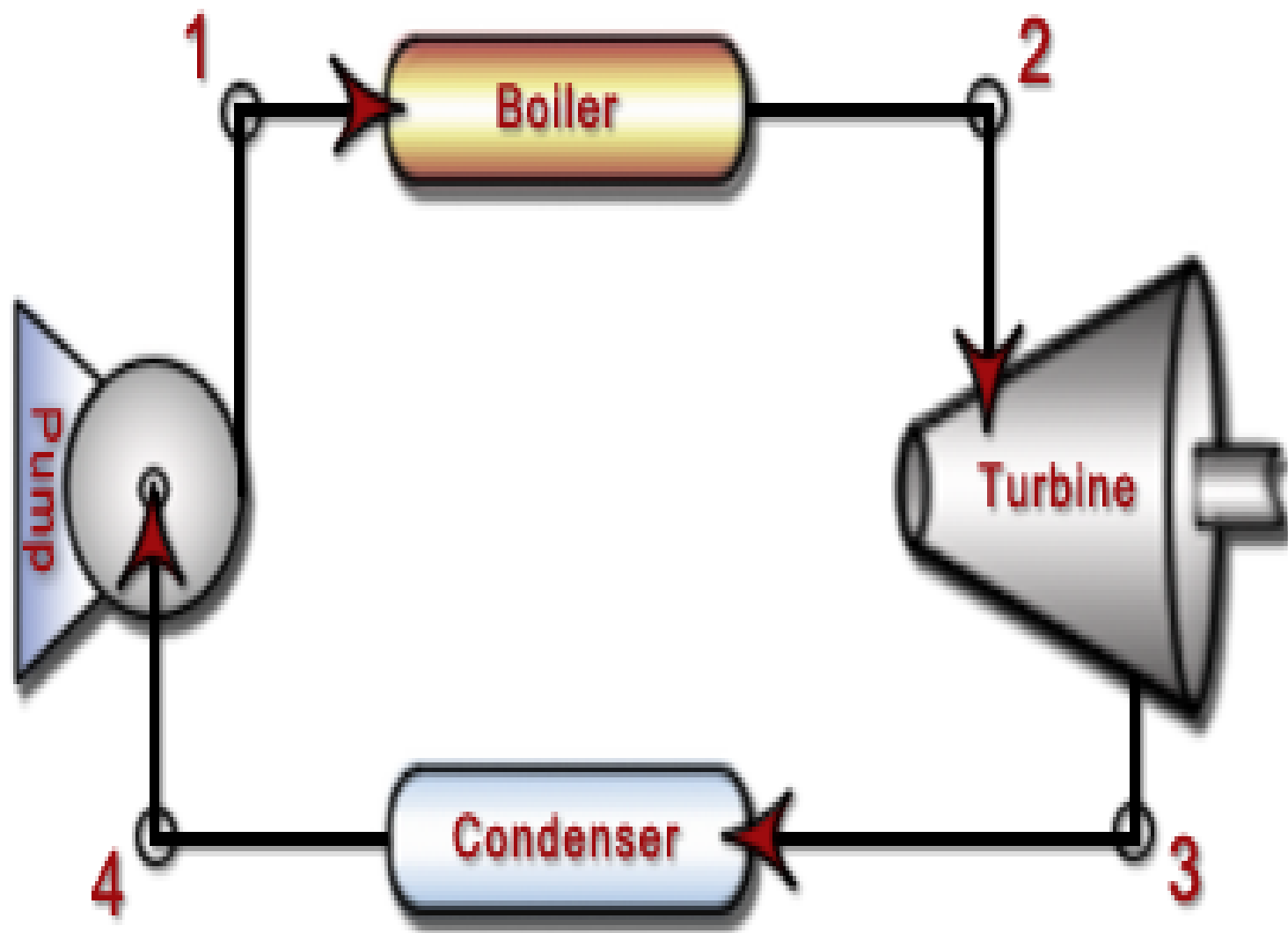
$$\text{Temperature of the hot reservoir, } T_1 = 273 + 127 = 400\text{K}$$

- (i) Efficiency of the engine, $\eta = 1 - (Q_2/Q_1) = 1 - (600/1000) = 0.4$
%age $\eta = 0.4 \times 100 = \mathbf{40\%}$
- (ii) $T_2/T_1 = Q_2/Q_1$
 $T_2 = Q_2/Q_1 \times T_1 = (600/1000) \times 400 = \mathbf{240 \text{ K}}$
- (iii) Useful Work = $Q_1 - Q_2 = 1000\text{J} - 600\text{J} = \mathbf{400\text{J}}$

Chapter two

steam power plant

2.02.2– Rankine cycle
improvement



introduction

- In real Rankine cycle, the compression by the pump & expansion in the turbine are not isentropic.
- In other words, these are non-reversible, and entropy is increased during the two processes.
- This will increase the power required by the pump, and at the same time decreases the power produced by the turbine.

Water droplets formation

- As the water condenses, water droplets hit the turbine blades at high speed causing “pitting & erosion”, and so, gradually decreasing the life and efficiency of the turbine.
- Therefore, it is very important to avoid condensation inside the turbine, which normally take place at the end portion of the expansion process

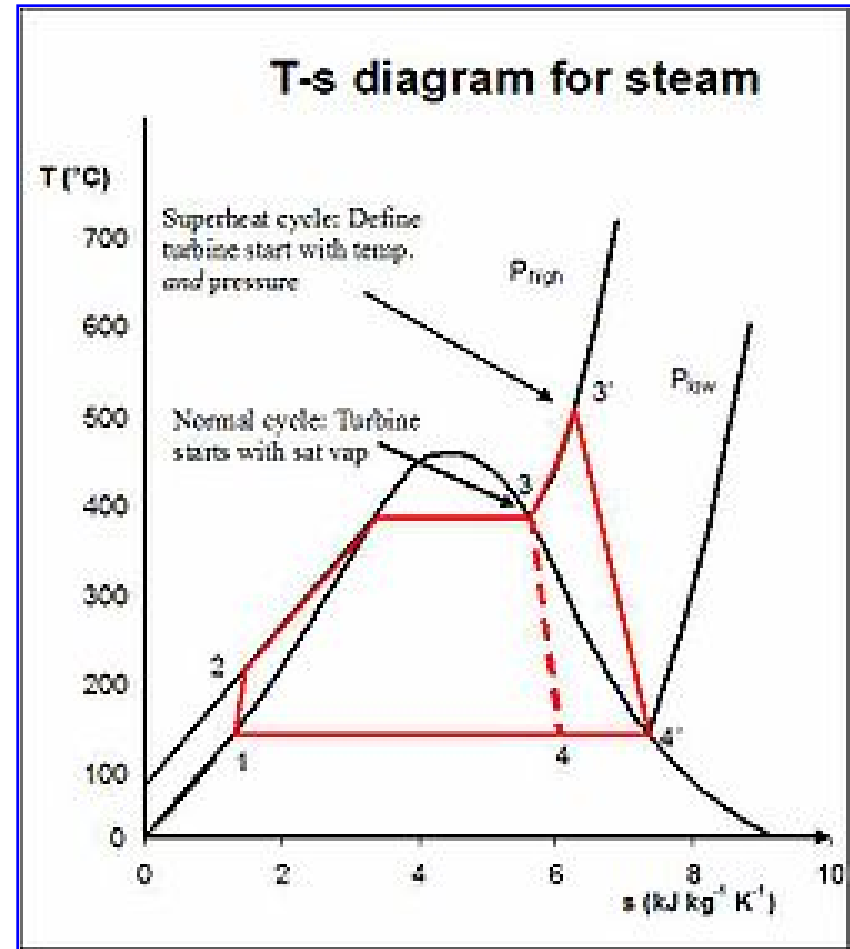
Consider this diagram in this respect, where state point (4) must be removed away from the wet region towards the vapor saturation line.

To do so, state point (3) must enter the superheat region, and therefore process line (34) will be shifted to the right causing state points :

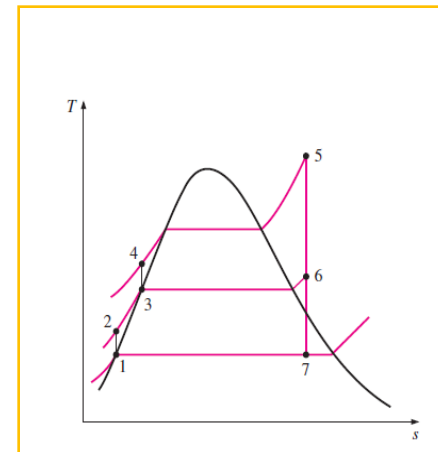
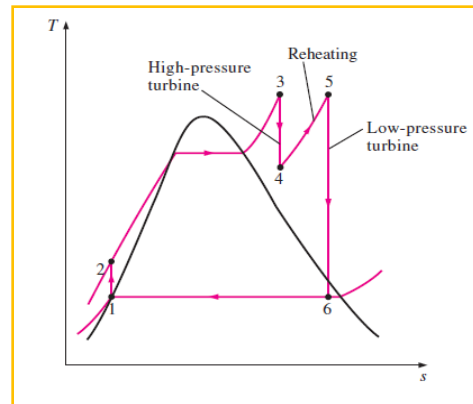
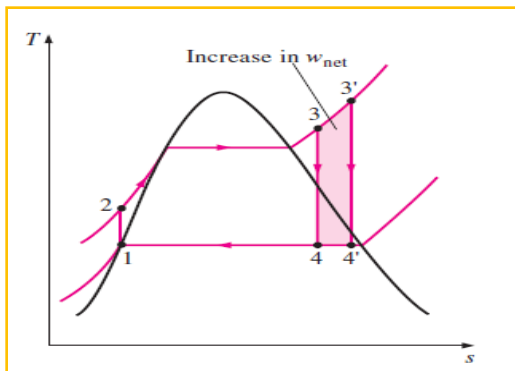
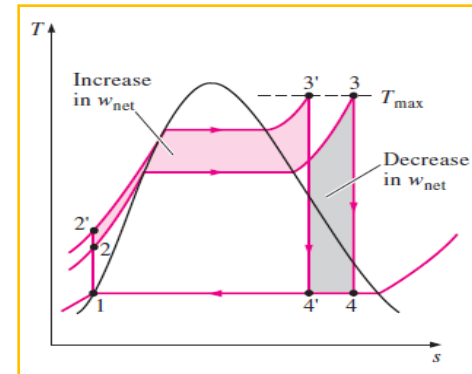
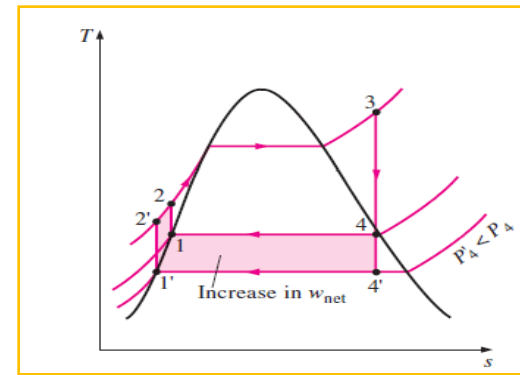
i / (3 $\rightarrow$ moves to superheat region to reach 3⁻)

ii / (4 $\rightarrow$ moves to vapor saturation line to reach 4⁻)

Such action improves cycle efficiency and protect turbine blades.

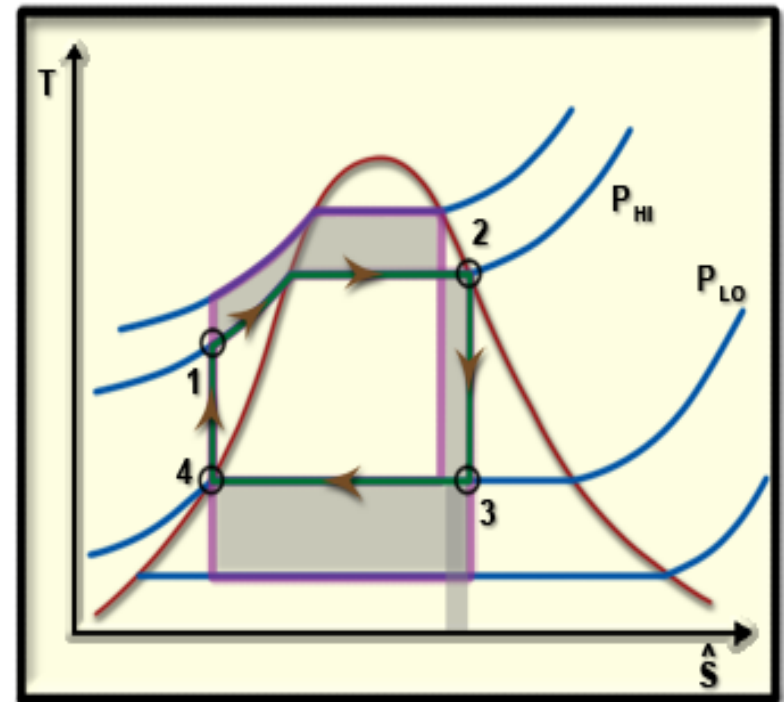


- In order to avoid above disadvantages and improve cycle efficiency, the followings are to be used wherever possible :
 - lowering the Condenser Pressure
 - Increasing the Boiler Pressure
 - cycle with superheat
 - cycle with reheat
 - cycle with regeneration
 - binary vapor cycle



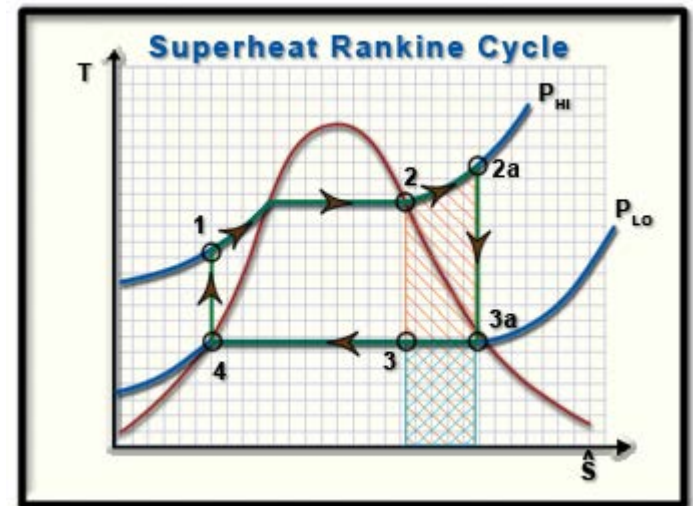
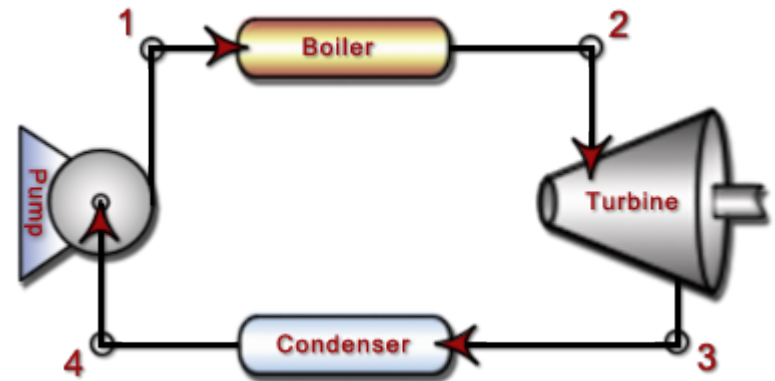
lowering condenser pressure increasing boiler pressure

- we can improve the efficiency of a Rankine power cycle by increasing the pressure of the boiler and by decreasing the pressure of the condenser.
- Unfortunately, this can lead to a dangerously low quality vapor in the turbine exhaust.
- The pump is safe from damage as long as the condenser outlet is a saturated or even sub-cooled liquid.
- So, keeping the quality of the turbine effluent above 90% is one of the main objectives of most of the methods we will discuss.



superheating

- In a **Superheat Rankine Cycle**, the boiler produces superheated vapor. This helps maintain a high quality vapor-liquid mixture at the turbine effluent.
- Because the high pressure isobar slopes upward outside of the two-phase envelope, Q_h increases by a larger percentage than Q_c increases. This is true as long as the turbine effluent is not superheated.
- The result is an increase in the **thermal efficiency** of the cycle and an increase in the quality of the turbine effluent !

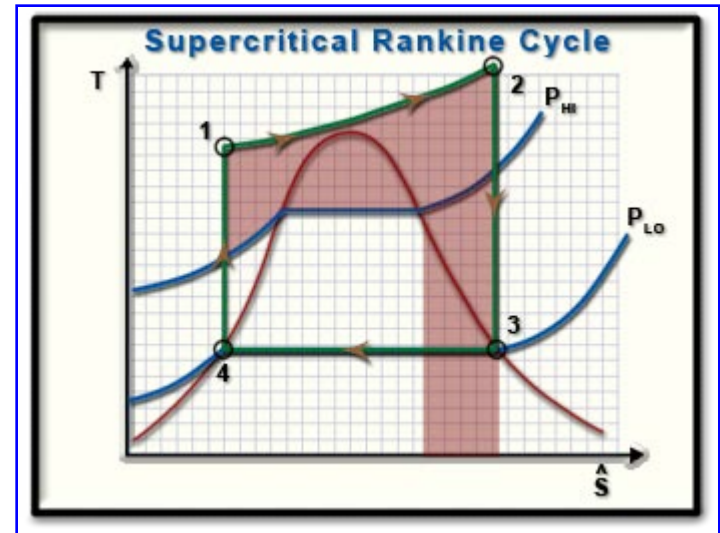
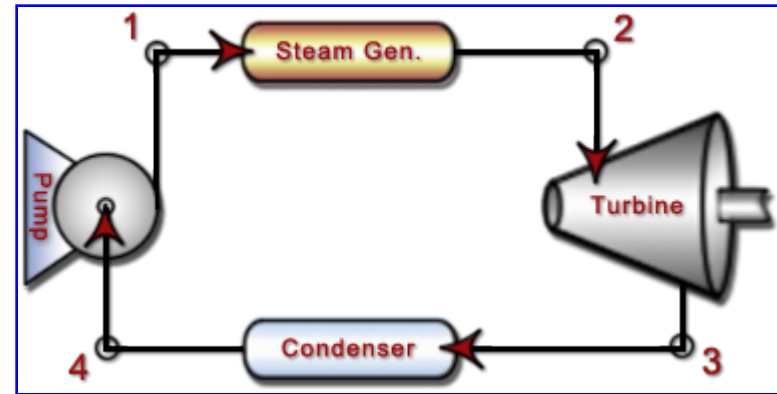


- When the boiler is operated to produce superheated steam, it is clear from the TS diagram that the quality of the turbine effluent increases.
- That is to say, as point 2 on the TS diagram slides along the isobar towards point 2a, the turbine effluent at point 3 moves towards point 3a where the quality approaches 1.0.
- how does superheat effect the efficiency of the cycle ?
- The area under the process path for the boiler increases rapidly as point 2 moves towards point 2a because the isobar slopes upward after it leaves the 2-phase envelope.
- The area under the path for the boiler is equal to Q_h , because the process is internally reversible.
- The area under the path for the condenser also increases as point 3 slides toward point 3a, but not as rapidly, because the path is a horizontal line.
- The area under the path for the condenser is equal to Q_c because the condenser is also internally reversible.
- Because the ratio of the CHANGE in Q_c to the CHANGE in Q_h is smaller than the ratio of Q_c to Q_h in the original Rankine Cycle, the efficiency increases when the boiler effluent is superheated.
- This is true because the thermal efficiency is $1 - Q_c / Q_h$.
- We conclude that superheat increases the thermal efficiency of the Rankine Cycle and actually improves the quality of the turbine effluent.
- In fact, superheat is so desirable that it is part of most of the other methods we will discuss.

Supercritical Rankine Cycle

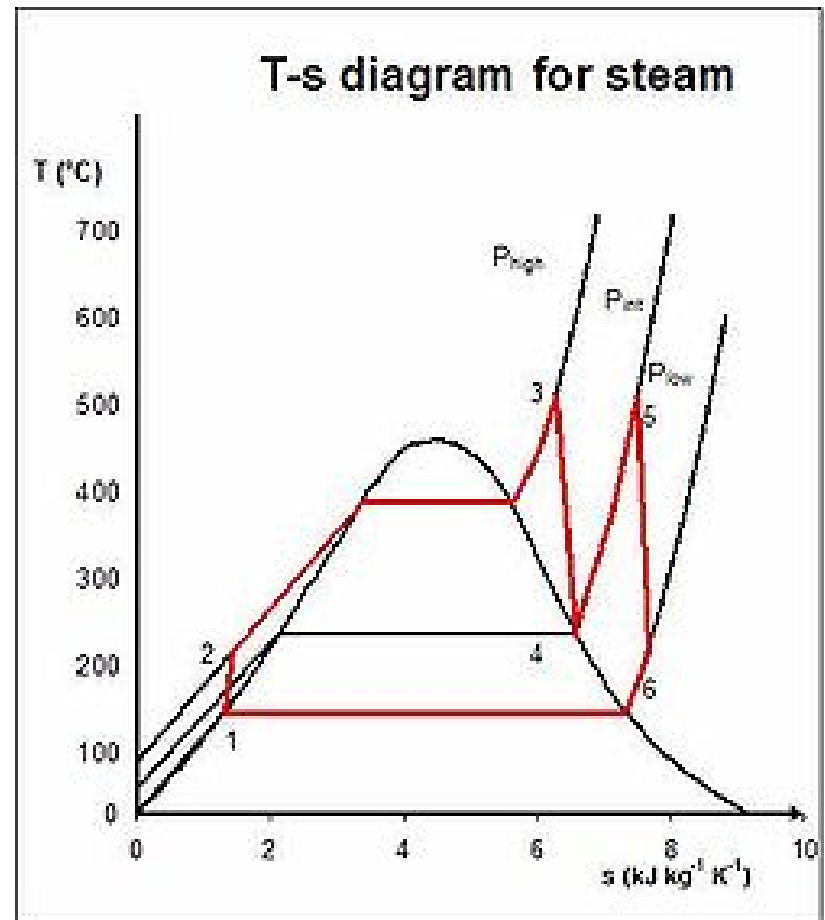
In a **Supercritical Rankine Cycle**, the operating pressure of the boiler is greater than the critical pressure of the working fluid.

The heat exchanger in which the working fluid absorbs heat from the hot reservoir is not always called a boiler. This heat exchanger, sometimes called a **steam generator**, produces a superheated vapor. The **thermal efficiency** of the cycle increases because Q_h increases greatly while Q_c increases very little. The majority of the additional heat input, relative to the **Rankine Cycle**, is converted into work. This method can also produce an increase in the quality of the turbine effluent.



Re-heat

- In this variation, two [turbines](#) work in series. The first accepts [vapor](#) from the [boiler](#) at high pressure. After the vapor has passed through the first turbine, it re-enters the boiler and is reheated (generally to the original temperature) before passing through a second, lower pressure turbine.
- Among other advantages, this prevents the vapor from [condensing](#) during its expansion which can seriously damage the turbine blades, and improves the efficiency of the cycle.



Advantages & disadvantages

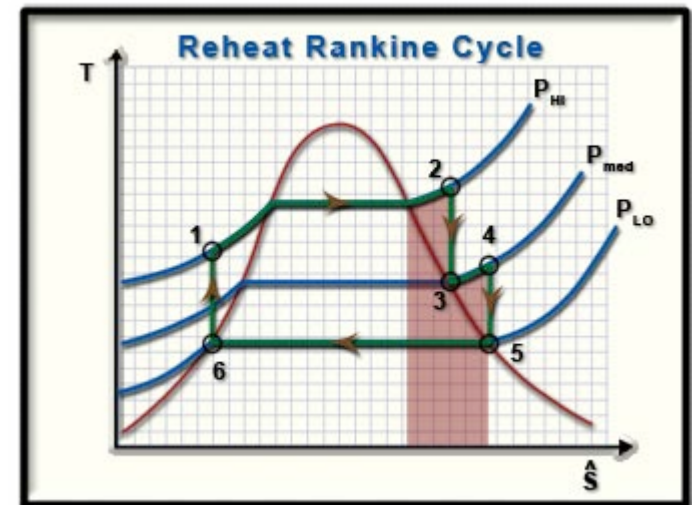
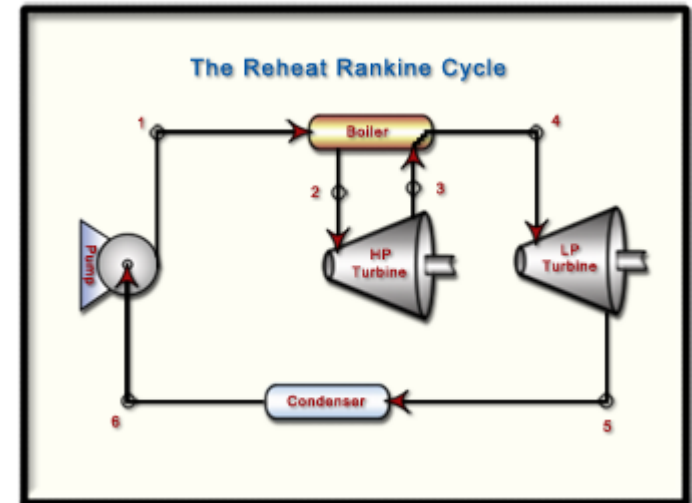
- Advantages

1. *Increases thermal eff.*
2. *Increases dryness fraction of the steam at turbine exhaust, this will reduce blade erosion.*
3. *Increase work done per unit mass of steam, thus reducing boiler size.*

- Disadvantages

1. *Increases plant cost due to re-heater requirement and it's long piping system.*
2. *Increases condenser capacity due to the increase in steam dryness fraction.*

- The reheat Rankine cycle uses two turbines to help avoid a low quality effluent.
- The superheated vapor leaving the boiler enters the high pressure turbine.
- The effluent from the high-pressure turbine returns to the boiler, where it is heated isobarically and then fed to the low-pressure turbine.
- The low-pressure turbine lets the pressure down to the pressure of the condenser.
- But, because of the reheat step between the two turbines, the quality at the low-pressure turbine effluent is quite high.

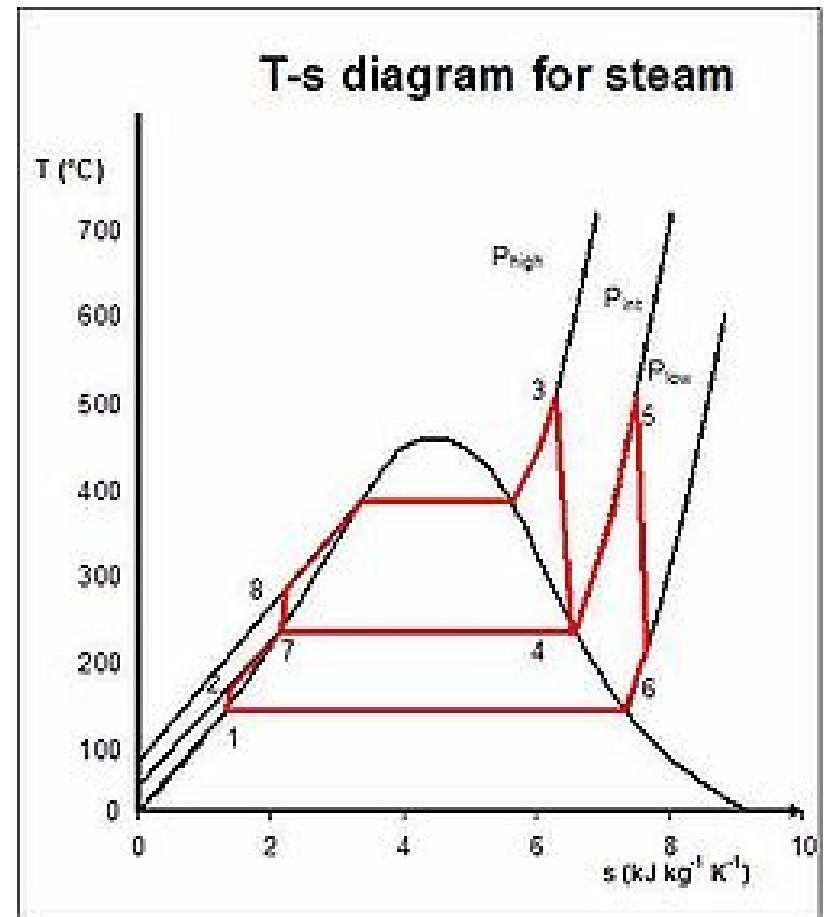


The TS diagram shows us that the reheat rankine cycle combines all of the advantages of of the superheat method with the simple method of increasing the boiler pressure and decreasing the condenser pressure.

- The result is an increase in Q_h and no change or even a decrease in Q_c . Both of these effects result in a significant increase in the thermal efficiency.
- At the same time, the quality of the effluent from the final turbine increased.
- Perhaps you noticed that the same advantages could be gained using just a superheat cycle.
- The difference is that both the boiler and the turbine must be able to operate at MUCH higher temperatures to achieve comparable results using a Rankine Superheat Cycle.
- So, the Rankine Reheat Cycle has some excellent characteristics.

regeneration

- The regenerative Rankine cycle is so named because after emerging from the condenser (possibly as a [subcooled liquid](#)) the working fluid is heated by [steam](#) tapped from the hot portion of the cycle. On the diagram shown, the fluid at 2 is mixed with the fluid at 4 (both at the same pressure) to end up with the saturated liquid at 7. The Regenerative Rankine cycle (with minor variants) is commonly used in real power stations.
- Another variation is where 'bleed steam' from between turbine stages is sent to [feedwater heaters](#) to preheat the water on its way from the condenser to the boiler.



In a **Rankine Cycle with Regeneration**, pumping the condenser effluent back up to the high pressure of the boiler is done in two stages. At the intermediate pressure between the two pumps, the working fluid is heated back to the saturated liquid state in the feedwater heater. The feedwater heater shown here is called an open feedwater heater because some of the effluent from the high pressure turbine actually mixes with the effluent from the first pump.

1-2 : Boiler - heat added at constant pressure.

2-3 : High-Pressure Turbine (HP) – isentropic expansion.

3-4,5 : Splitter - stream 3 is split into streams 4 and 5.

5-6 : Low-Pressure Turbine (LP)- isentropic expansion

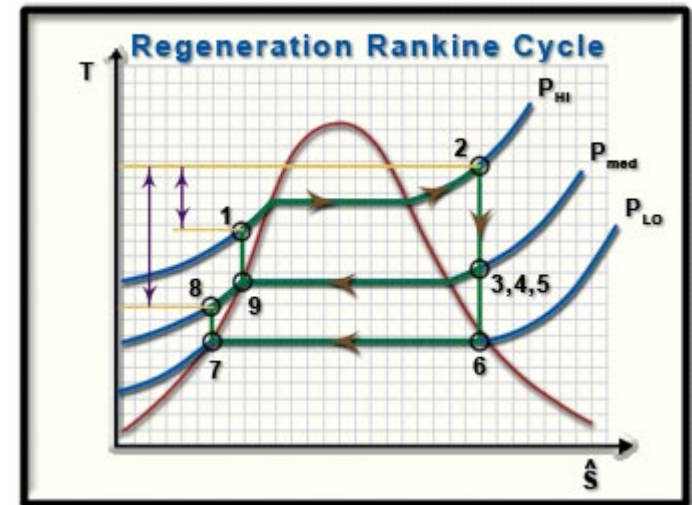
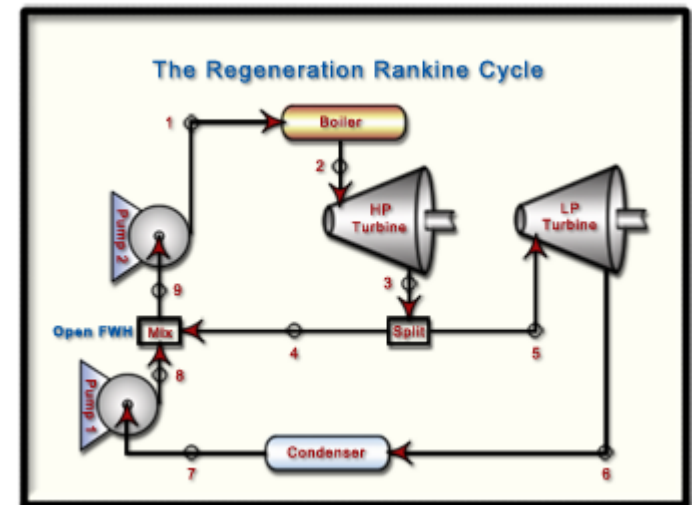
6-7 : Condenser - heat rejected at constant pressure.

7-8 : Pump #1 - isentropic compression.

8-9 : Feedwater Heater (FWH) - temperature increases by mixing.

4-9 : Feedwater Heater (FWH) - temperature decreases by mixing

9-1 : Pump #2- isentropic Compression.

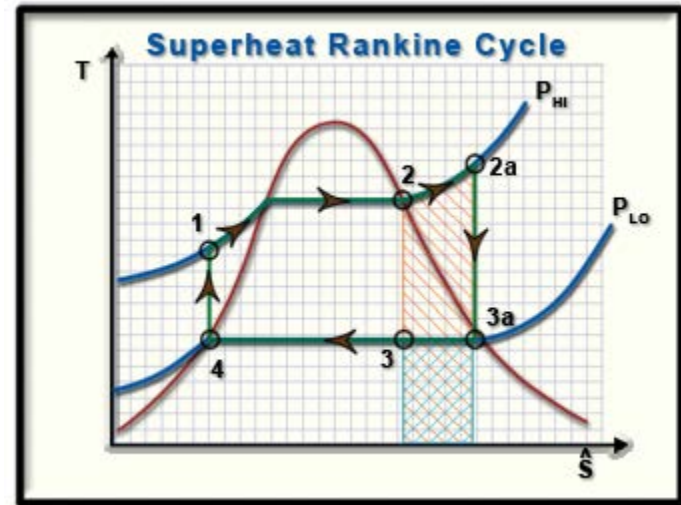


Performance evaluation

- The performance of each plant component can be expressed in term of enthalpy drop between it's inlet and outlet for unit mass.
- The two basic components are :
 1. Turbine → produces useful work output
 2. Boiler → provides heat energy input.
- And so, for each step of improvement; work output, heat input, and thermal energy can be evaluated as follows :

Rankine cycle with superheat

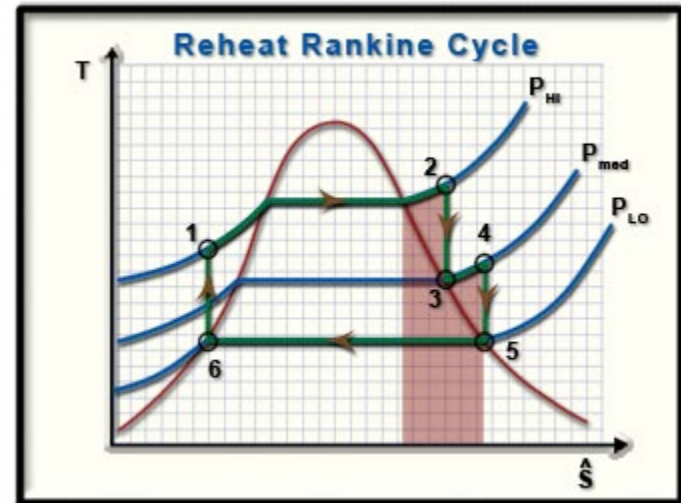
- $\dot{W} = h_{2a} - h_{3a}$
- $Q_{in} = h_{2a} - h_1$
- $\eta_{th} = (h_{2a} - h_{3a}) / (h_{2a} - h_1)$



Rankine cycle with reheat

- $\dot{W} = (h_2 - h_3) + (h_4 - h_5)$
- $Q_{in} = (h_2 - h_1) + (h_4 - h_3)$

$$\eta_{th} = \left(\frac{[h_2 - h_3] + [h_4 - h_5]}{[h_2 - h_1] + [h_4 - h_3]} \right)$$



Rankine cycle with regeneration

$$Q_{in} = (1)(h_2 - h_1)$$

$$Q_{out} = (1 - y)(h_6 - h_7)$$

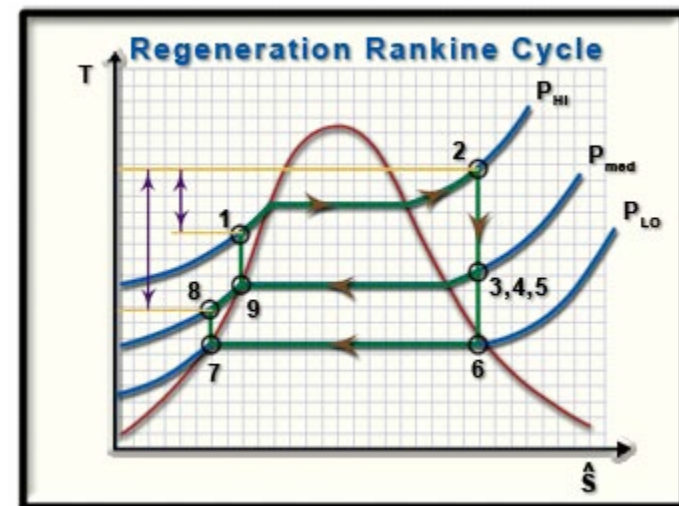
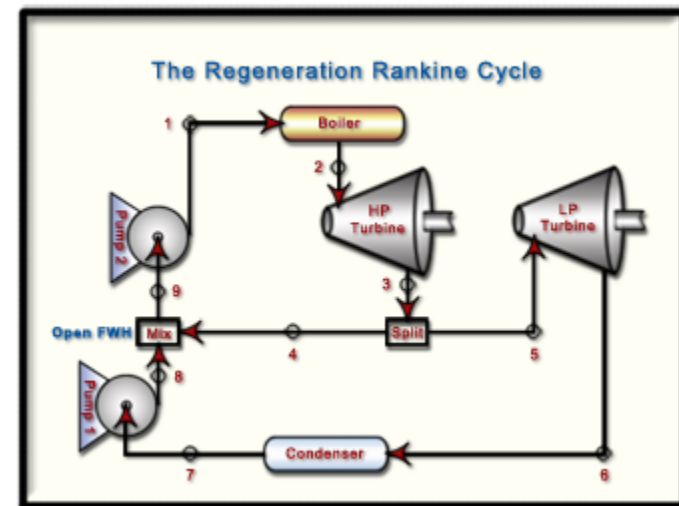
$$W_{tur} = (1)(h_2 - h_3) + (1 - y)(h_5 - h_6)$$

$$W_{pump} = W_{p1} + W_{p2}$$

$$W_{pump} = (1 - y)(W_{p1}) + (1)(W_{p2})$$

y : fraction of steam extracted

$$y = \frac{\dot{m}_4}{\dot{m}_3}$$



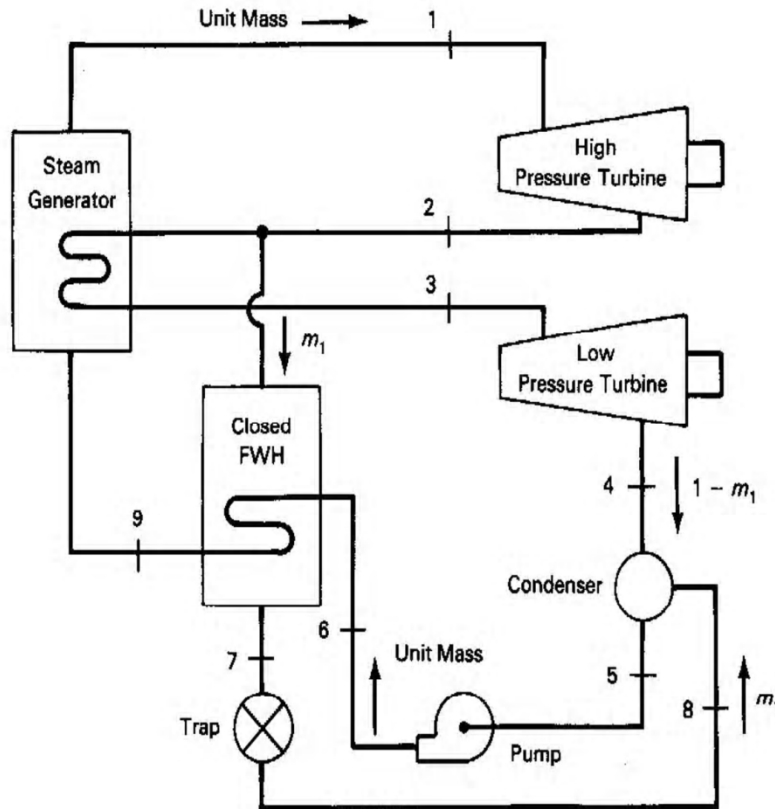
Extracted steam temperature

Also, sometimes it is required to know the extracted steam temperature to determine the extracted steam pressure.

This temperature may be approximated as mean values of the temperature at condenser entrance (T_6), and at boiler entrance (T_1)

$$T_{extracted} = \frac{T_6 + T_1}{2}$$

In general for a large power plant, all these methods of plant improvement can be applied at the same time as can be seen from this schematic diagram of such a plant



Home work

- Fill-in the expressions required in the table below derived from one common T-s diagram; thus showing the cycle improvement on both these expressions and the T-s diagram

	Work output	Heat supplied	Thermal eff.
Standard cycle			
Superheated cycle			
Reheat cycle			
regeneration			

Chapter two

steam power plant

2.02.2E – The supercritical
Rankine cycle

The Rankine is a general cycle for the steam power plant. However, such cycles have been modified to a superheated version to improve system performance. Further improvement is the supercritical pressure of critical cycle. Supercritical range of boilers is that they have pressure in excess of the (221.2) bar. It is important to note that when the water is heated in the boiler at pressure above the critical at constant pressure, the temperature is never constant, and no distinction between the gaseous (vapor) and liquid states can be observed as shown in the T-s diagram below

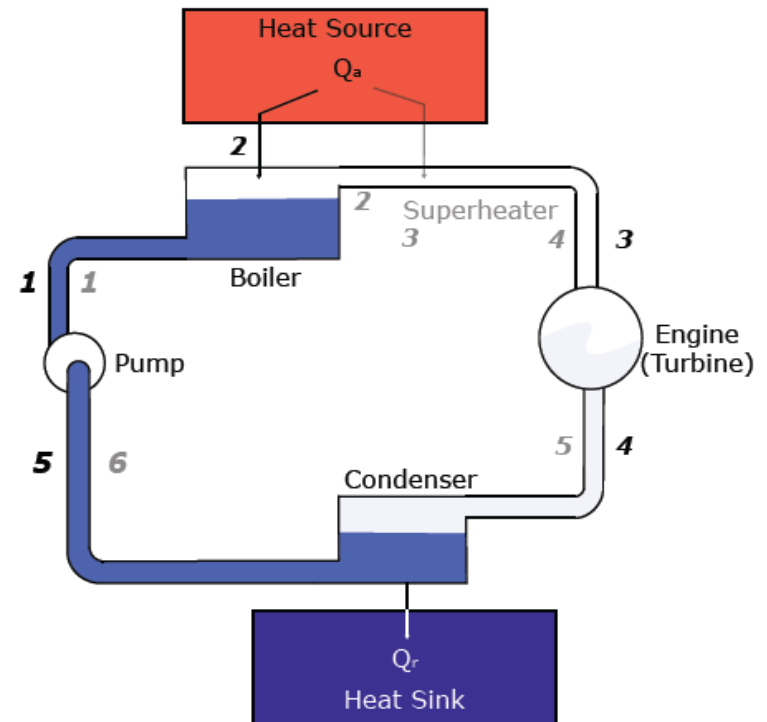
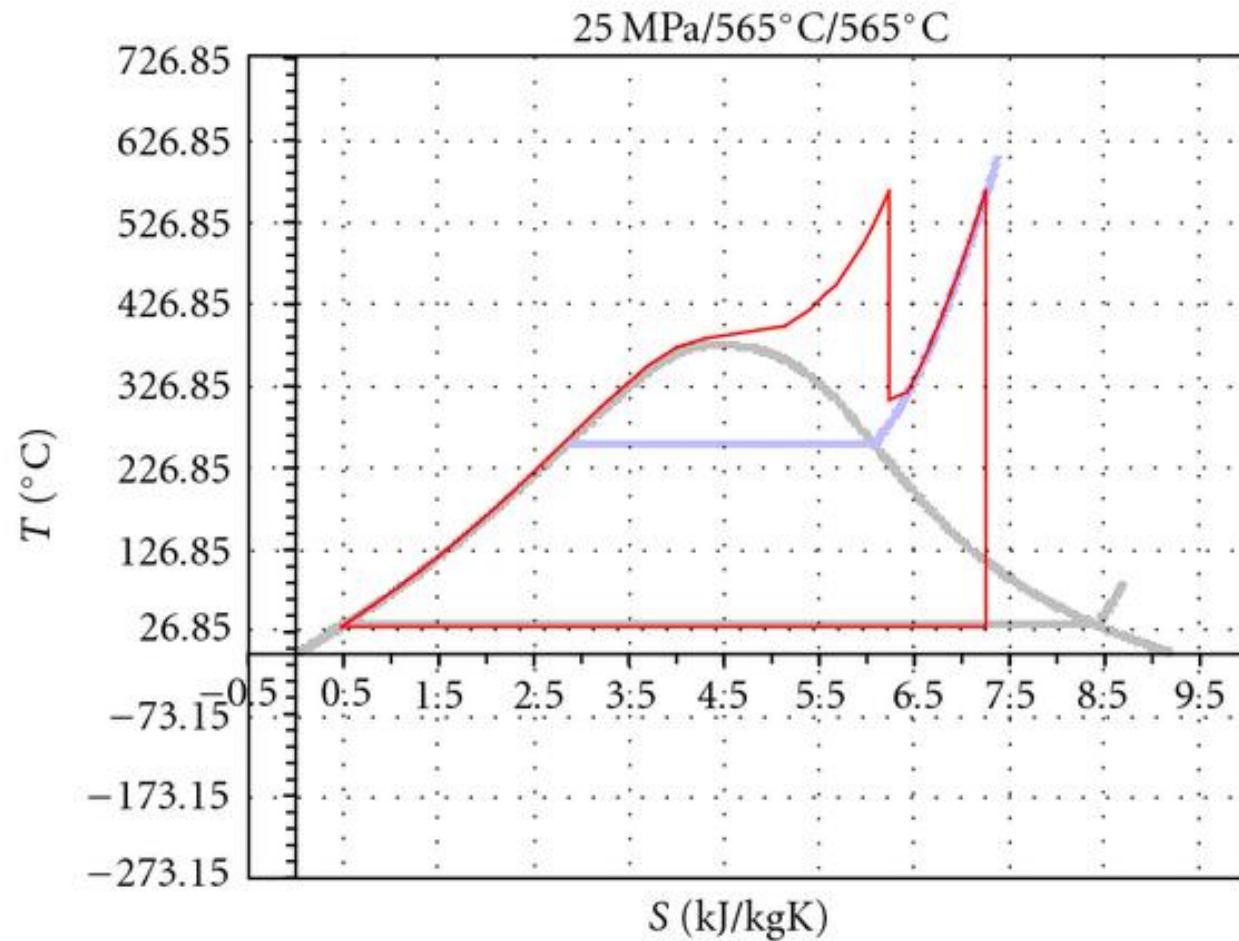


Figure 1. Simple Rankine/Steam Cycle
Black numbers correspond to Figure 2;
Grey numbers correspond to Figure 3.

Supercritical cycle T-s diagram



Useful remarks

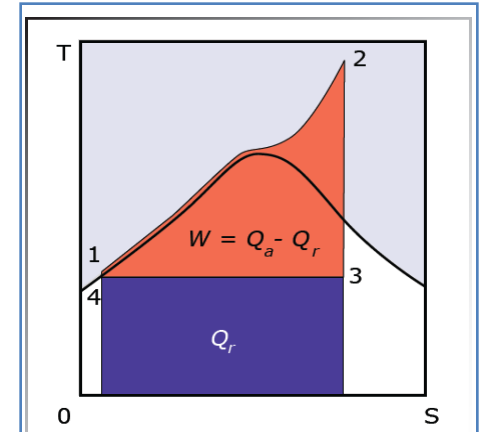
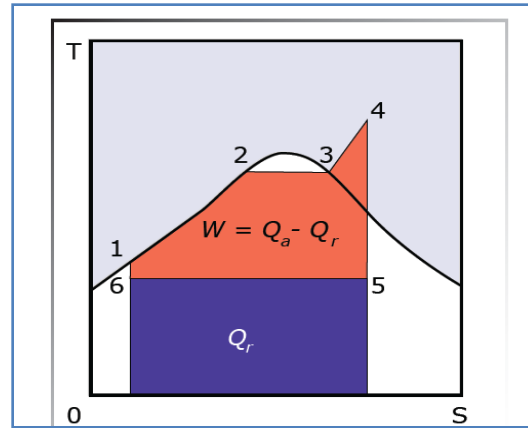
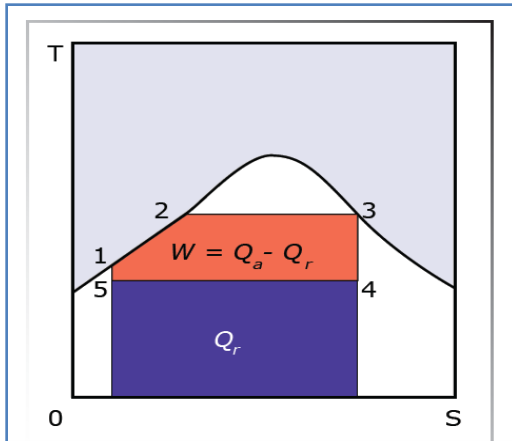
The Rankine cycle and variation of the Rankine cycle presented so far have involved heat addition during vaporization process . This heat transfer process occurs at a relatively low temperature (around say 250°C) at a pressure of (4 MPa), yet the hot gases surrounding the boiler after combustion are around (2500°C). This large temperature difference makes the heat transfer quite irreversible (recall that to approach reversibility the heat transfer process must occur over a small temperature difference).

Hence to improve the plant efficiency it is desirable to increase the temperature at which the heat transfer takes place. This will also improve the cycle efficiency since the area representing the work will increase.

To get closer to the Carnot cycle efficiency, the temperature of the working fluid should be as near the temperature of the hot gases as possible

The SUPERCRITICAL Rankine cycle accomplishes this .

Supercritical cycle



- The Supercritical Rankine Cycle is basically a superheat Rankine Cycle in which the operating pressure of the boiler is greater than the critical pressure of the working fluid .
- This method generally provides a bigger increase in the efficiency than the superheat cycle while still maintaining high quality in the turbine effluent .
- The drawback is that the boiler and turbine must be built to withstand high pressure and high temperatures and this can be quite expensive .

Chapter two

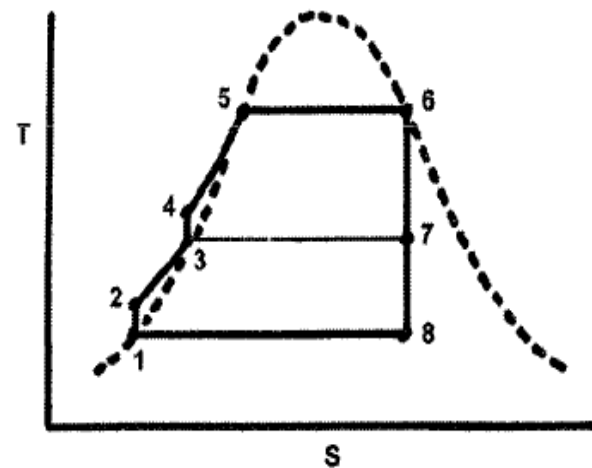
steam power plant

2.02.3 – Feed-Water Heater
OFWH & CFWH

REGENERATIVE FEEDWATER HEATING

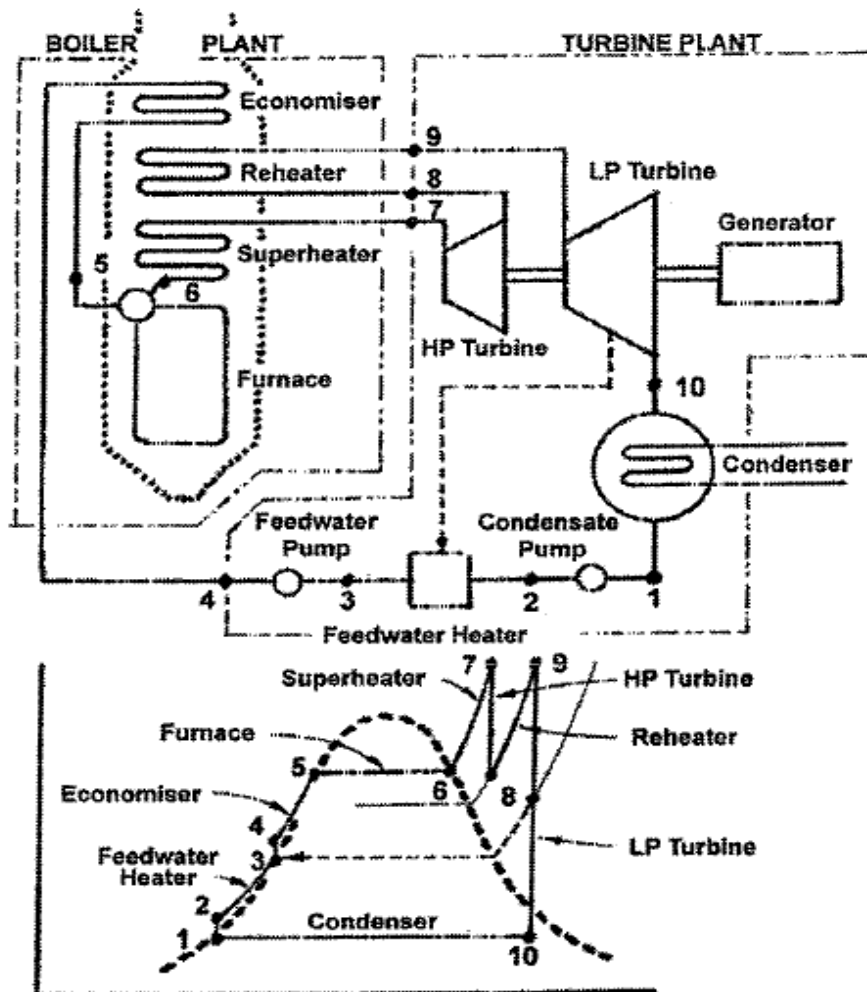
It was noted when introducing the Rankine Cycle that the ideal Rankine Cycle was not as thermodynamically efficient as the ideal Carnot Cycle when operating between the same upper and lower temperature limits. It should be noted that, in the Rankine Cycle, heat is added from the boiler immediately after pumping to a high pressure. Since there is very little temperature rise in the pump some heat is added at temperatures below the upper temperature. This leads to a reduction of the average temperature of heat addition and hence a lower cycle efficiency than exhibited by the Carnot Cycle which receives all its heat at the upper temperature.

EFFICIENCY IMPROVEMENT WITH FEEDWATER HEATING

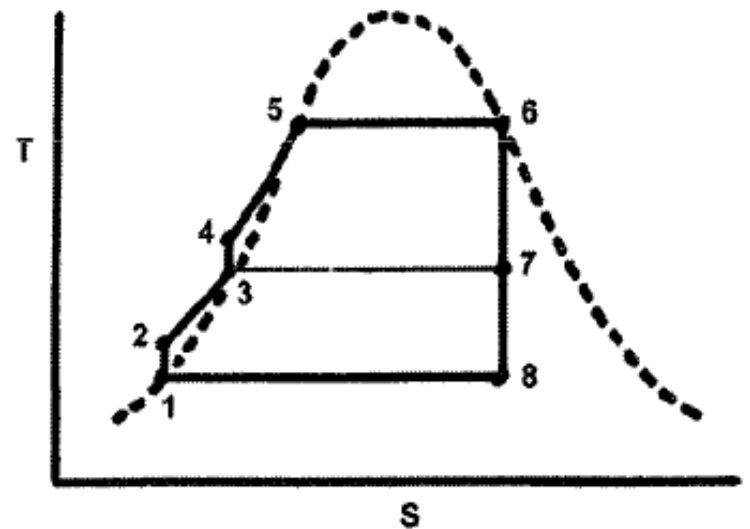


- Some heat transferred to feedwater from 2 to 3
- Slightly less work produced in turbine from 7 to 8
- Slightly less heat rejected in condenser from 8 to 1
- Heat added in boiler only from 4 to 6
- Closer to Carnot Cycle therefore higher efficiency
- With multiple heaters more feedwater heating
- In limit boiler adds heat only from 5 to 6
- Equal to Carnot Cycle therefore maximum efficiency.

BOILER - TURBINE UNIT



EFFICIENCY IMPROVEMENT WITH FEEDWATER HEATING



- Some heat transferred to feedwater from 2 to 3
- Slightly less work produced in turbine from 7 to 8
- Slightly less heat rejected in condenser from 8 to 1
- Heat added in boiler only from 4 to 6
- Closer to Carnot Cycle therefore higher efficiency
- With multiple heaters more feedwater heating
- In limit boiler adds heat only from 5 to 6
- Equal to Carnot Cycle therefore maximum efficiency.

Direct contact FWH

This is more commonly known as open feed-water heater (OFWH), which allows mixing of the extracted steam with feedwater to be heated.

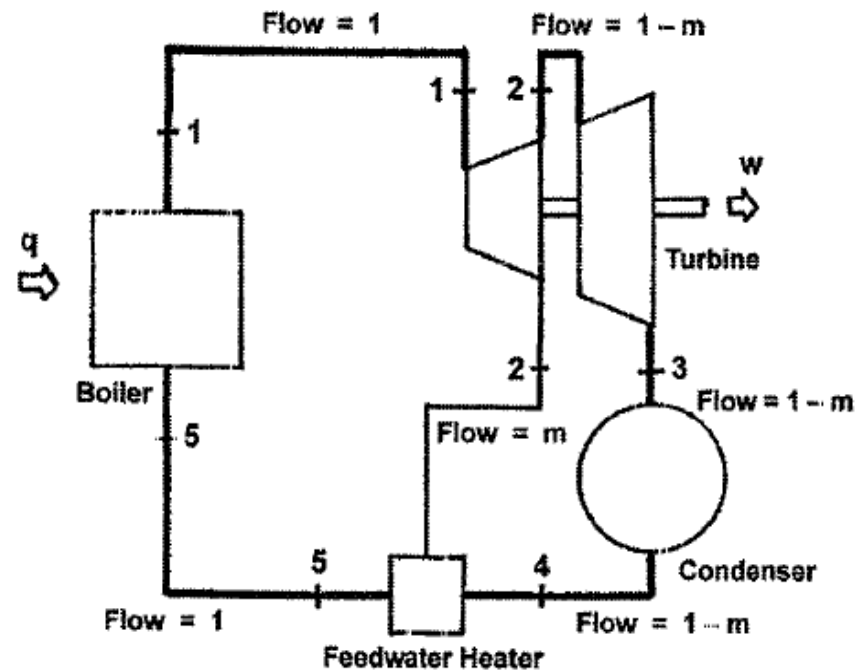
This is done by an arrangement of spray nozzle and trays to distribute the water evenly and in fine droplet forms throughout the steam space.

The water is heated by the steam which condenses and both leaves together as a single flow towards the boiler.

in order to facilitate the mixing, and since the extracted steam is normally at higher pressure than feed-water from condenser, then a pump is required in the feed-water line before the FWH to raise the feed water pressure up to that of the extracted steam.

FEEDWATER HEATING

DIRECT CONTACT HEATER



$$m (h_2 - h_3) = (1 - m) (h_5 - h_4)$$

$$m (h_2 - h_3) = (h_5 - h_4) - m (h_5 - h_4)$$

$$m (h_2 - h_3) + m (h_5 - h_4) = (h_5 - h_4)$$

$$m = (h_5 - h_4) / (h_2 - h_3 + h_5 - h_4)$$

$$m = (h_5 - h_4) / (h_2 - h_4)$$

$$q = 1 (h_1 - h_5)$$

$$w = 1 (h_1 - h_2) + (1 - m) (h_2 - h_3) - (\text{pump work})$$

$$\eta = w / q$$

Surface FWH

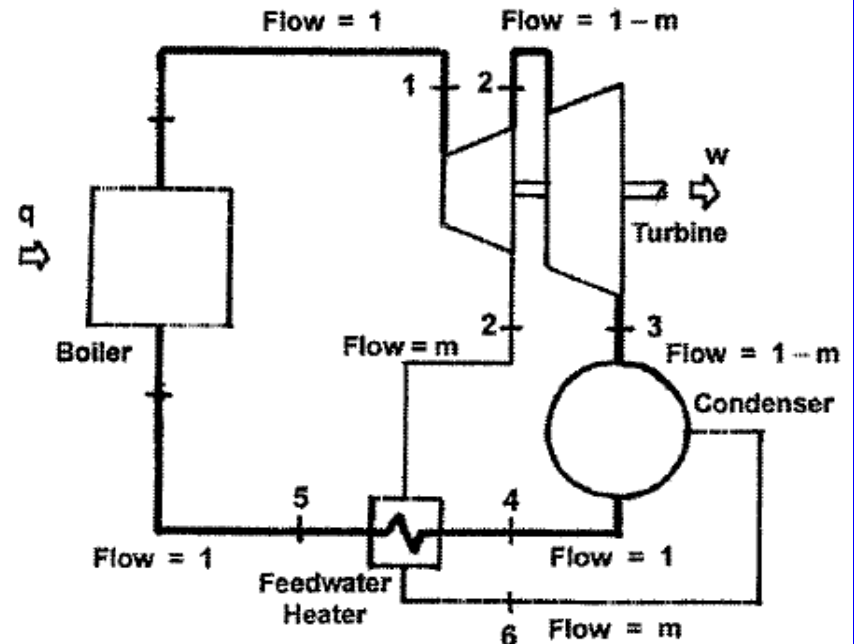
this is a closed type FWH (CFWH), which is simply a shell & tube heat exchanger.

The two streams (extracted steam & feed water) are kept separate in a separate flow lines, where the feed water passes through multiple tubes, while steams condenses on the outside them.

The condensed steam is drained back to the condenser as water.

FEEDWATER HEATING

SURFACE (TUBED) HEATER



$$m (h_2 - h_6) = (1) (h_5 - h_4)$$

$$m = (h_5 - h_4) / (h_2 - h_6)$$

$$q = 1 (h_1 - h_5)$$

$$w = 1 (h_1 - h_2) + (1 - m) (h_2 - h_3) - (\text{pump work})$$

$$\eta = w / q$$

Large steam power plants may have a series of FWH.

The calculation of the cycle eff. on such plant is no more different than that for one with a single heater, but rather tedious.

Each heater has a different mass flow rate, which must be calculated by doing mass balance on each one.

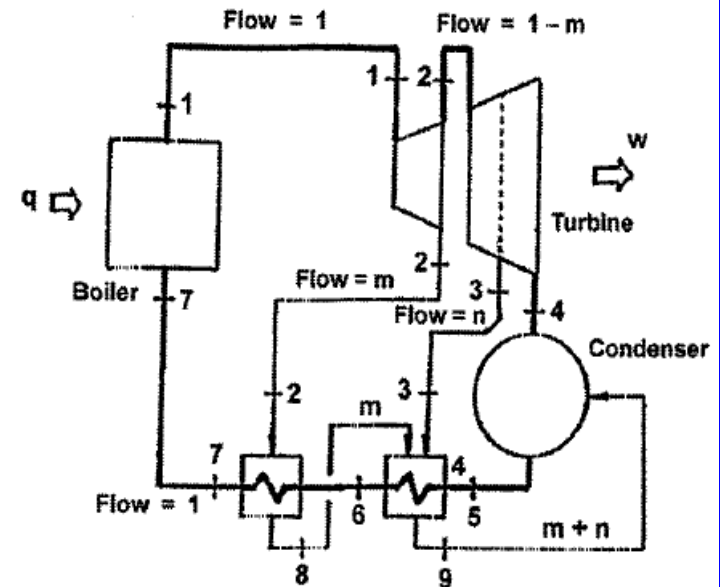
Usually condensed steam drain flow is cascaded down to the next lower pressure FWH, and finally to the condenser.

The heat balance between heaters are therefore linked through a series of simultaneous equations.

The cycle efficiency is the work from each section of the turbine minus the pump work all divided by the heat input from the boiler.

FEEDWATER HEATING

MULTIPLE HEATERS



$$m(h_2 - h_8) = 1(h_7 - h_6)$$

$$m = (h_7 - h_6) / (h_2 - h_8)$$

$$n(h_3 - h_9) + m(h_8 - h_9) = 1(h_6 - h_5)$$

$$n = [(h_6 - h_5) + m(h_8 - h_9)] / (h_3 - h_9)$$

$$q = (h_1 - h_7)$$

$$w = 1(h_1 - h_2) + (1 - m)(h_2 - h_3) + (1 - m - n)(h_3 - h_4) \\ - (\text{pump work})$$

$$n = w / q$$

$$\text{cycle eff.} = \frac{\text{work from each section of the turbine} - \text{pump work}}{\text{heat input from boiler}}$$

$$\eta = (\sum W_{\text{turbine}} - W_{\text{pump}}) / (q_{\text{boiler}})$$

FWH heat balance

It is very important for plant cycle analysis to specify the extracted steam mass flow rate. To calculate the steam mass flow required to heat up the feed-water, a heat and mass balance is carried out on the heater

$$M_{steam} \cdot \Delta h_{steam} = M_{feedwater} \cdot \Delta h_{feedwater}$$

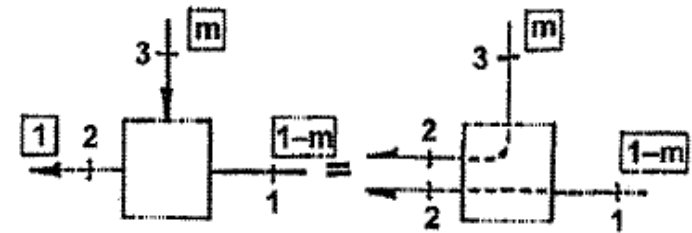
Such mass rate is generally handled as fraction values.

If unit mass rate of steam flow from boiler, and the extracted steam flow to heater is (m), then the balance leaving the turbine is (1-m), and so the heat balance will be :

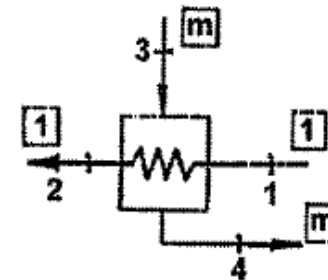
$$m \cdot \Delta h_{steam} = (1 - m) \cdot \Delta h_{feedwater} \quad \text{for OFWH}$$

$$m \cdot \Delta h_{steam} = (1) \Delta h_{feedwater} \quad \text{for CFWH}$$

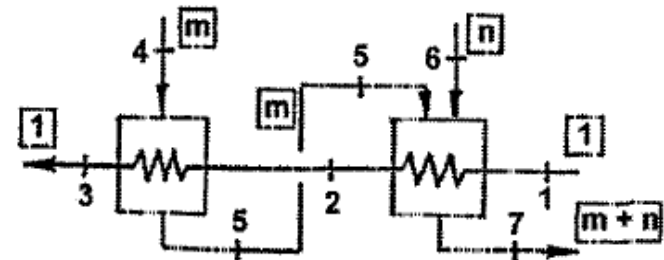
HEATER HEAT BALANCE



$$m (h_3 - h_2) = (1 - m) (h_2 - h_1)$$



$$1 (h_2 - h_1) = m (h_3 - h_4)$$



$$m (h_4 - h_5) = 1 (h_3 - h_2)$$

$$m (h_6 - h_7) + n (h_6 - h_7) = 1 (h_2 - h_1)$$

Power & efficiency

- If steam is drawn for example from the turbine extraction port which is at part way through it's expansion, the work done in the turbine is as follows :*

$$W_{tur} = [(1)(\Delta h_{1st\ part})] + [(1 - m)(\Delta h_{2nd\ part})]$$

- The heat input to the boiler is given by:*

$$Q_{boiler} = (1)(\Delta h_{boiler})$$

- And the cycle efficiency then becomes :*

$$\eta_{cycle} = \frac{W_{tur} - W_{pump}}{Q_{boiler}}$$

Chapter two

steam power plant

2.02.4 – Binary cycle

Binary Vapor Cycles

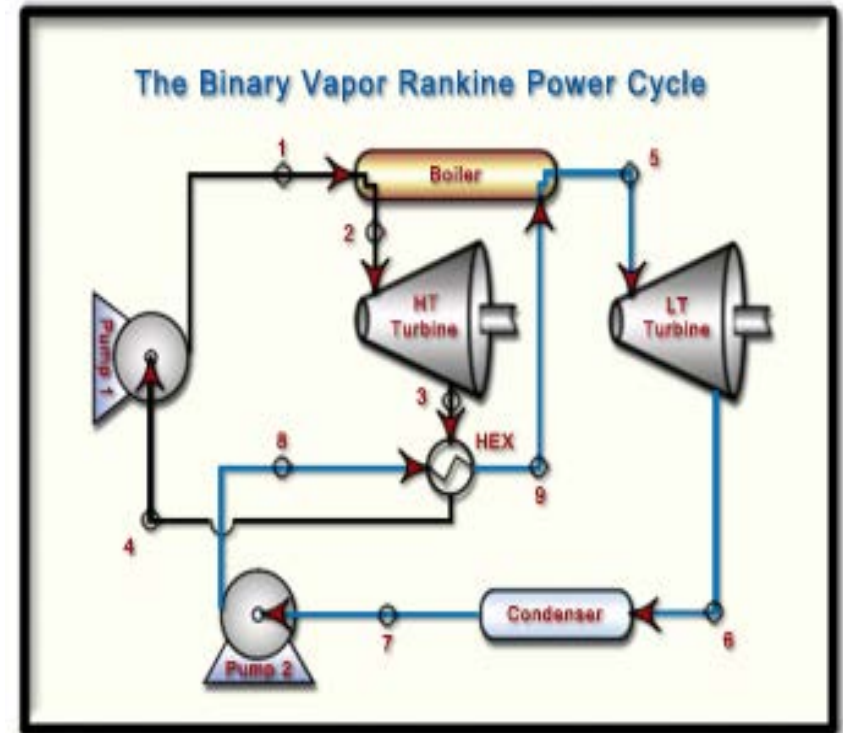
- **A Binary Vapor Rankine Power Cycle consists of two separate Rankine Vapor Power Cycles that use different working fluids.**
- The two cycles only interact through a shared heat exchanger (HEX).
- In this heat exchanger, the subcooled liquid leaving the pump in the low-temperature cycle absorbs heat from the turbine effluent of the high-temperature cycle.

High-Temperature Rankine Cycle

- 1-2: Boiler - Heat added at constant pressure.
- 2-3: Turbine #1 - Isentropic expansion.
- 3-4: HEX - Heat rejected at constant pressure.
- 4-1: Pump #1 - Isentropic compression.

Low-Temperature Rankine Cycle

- 5-6: Turbine #2 - Isentropic expansion.
- 6-7: Condenser #2 - Heat rejected at constant pressure.
- 7-8: Pump #2 - Isentropic compression
- 8-9: HEX - Heat added at constant pressure.
- 9-5: Boiler - Heat added at constant pressure.



- A binary vapor power cycle is two power cycles working together.
- The high-temperature cycle absorbs heat from the hot reservoir and the low-temperature cycle rejects heat to the cold reservoir.
- The interesting part is that the heat rejected from the high-temperature cycle, Q_{C1} is used as the heat INPUT to the low-temperature cycle, Q_{H2} .
- The transfer of heat out of the high-temperature working fluid and into the low temperature working fluid takes place in a heat exchanger, labeled "HEX" in the diagram.
- If the flow rates of the two working fluids are controlled properly, the low-temperature cycle does not need to receive heat from the boiler, otherwise, the low temperature working fluid can be heated further in the boiler as shown here.
- The key is that the working fluids in the two cycles CANNOT be the same. If the two working fluids were the same, there would be no advantage to using a binary vapor cycle.

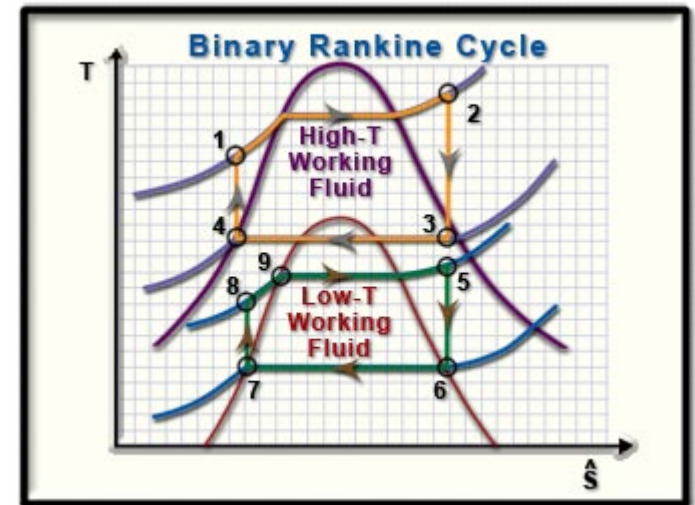
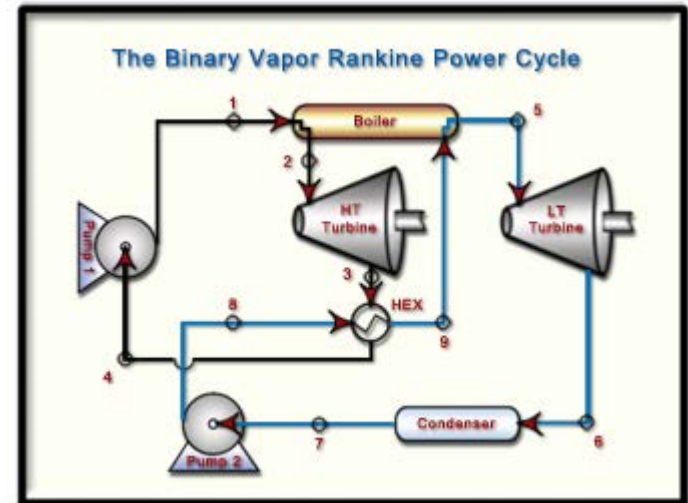
T- s Diagram for a Binary Vapor Cycle

The high-temperature working fluid has a lower saturation pressure for any given temperature. Therefore, the upper cycle runs at a higher temperature, but not necessarily at a higher pressure than the lower temperature cycle.

The key is that the temperature of the high-temperature turbine effluent (T_3) must be greater than the saturation temperature of the fluid leaving the pump in the low-temperature cycle ($T_{sat} @ P_8$).

Ideally, for steady heat transfer, the heat input to the low temperature cycle is obtained from the heat rejected from the high temperature cycle:

$$T_4 - T_9 = T_3 - T_5$$



- The first thing you notice about this TS Diagram is that there are TWO two-phase envelopes.
 - The upper one is for the working fluid in the high-temperature cycle and the lower one is for the working fluid in the low-temperature cycle.
 - This means that the working fluid in the high temperature cycle must be heated to a higher temperature before it boils.
 - Another way to say this is that the working fluid in the high-temperature cycle is LESS VOLATILE than the working fluid in the low temperature cycle.
 - A good combination of working fluids might be mercury and water. Because the normal boiling point of mercury is 630 K compared to 373 K for water, the mercury would be the working fluid in the high-temperature cycle.
 - There is a large enough difference in the volatility of mercury and water that the saturation temperature of the mercury at the outlet of turbine T1 is greater than the saturation temperature of water at the outlet of pump P2.
 - As long as T3 exceeds T9 by about 10 °C, the heat exchanger will work well.
 - However, if you plan to use superheat in the low-temperature cycle, and T3 is not greater than T5, then the low temperature working fluid must absorb some heat from the boiler before entering turbine T2.
- Now, this seems like an elaborate process compared to the others we have considered

What are the advantages of a binary vapor power cycle?

- Because the high-temperature cycle absorbs heat at a very high temperature, its thermal efficiency is higher.
- Also, the heat source for the boiler is often a fuel of some type and its temperature is generally extremely high.
- By using a working fluid that has a high saturation temperature the irreversibility associated with transferring heat from the high temperature reservoir to the working fluid can be reduced.
- This also yields a more efficient cycle.
- The deciding factor is whether the increase in efficiency is great enough to offset the increased cost of building and operating the more complex system. As usual economic factors govern the design choice

Characteristics of working fluid

Working fluid most suitable for vapor power cycle must be characterized by :

1. High critical temperature improves isothermal heat transfer at ($T_{\max}$) as fluid changes phase.
2. Save maximum pressure, as very high pressure at ($T_{\max}$) is undesirable due to material strength problem.
3. Condenser pressure (not very low) usually operates below atmospheric. Too low condenser pressure causes leakage into the system which is undesirable.
4. High enthalpy of vaporization (h_{fg})
5. Good heat transfer characteristics.
6. Inert; inexpensive; available; non-toxic

Water is the best fluid that has characteristics close to those.

Rankine cycle efficiency improves with temperature. But there is a limit of such temperature imposed by construction material of (boiler & turbine).

Construction material thermal stress set such temperature limits at about ($600\text{ }^{\circ}\text{C}$) as max value .

Heat required to change saturated liquid to dry saturated vapor in the latent heat, and this appears in steam tables as (h_{fg})

For ($h_{fg} = 0$) , means that no heat is required to change phases, and that critical point is reached.

Reasons for binary system

**Critical point for steam is :

critical temperature = $374.15\text{ }^{\circ}\text{C}$

saturation pressure = 212.2 bar

**Critical temperature of steam is well below the maximum temperature limits imposed by construction material ($600\text{ }^{\circ}\text{C}$) .

**Therefore, there still a reasonable working space in terms of temperature limit if other working fluid is chosen instead of steam.

**this other working fluid must have critical temperature well above ($600\text{ }^{\circ}\text{C}$) and low corresponding saturation pressure in order to make use of it's (h_{fg}) within the saturation dome of it's (T-s) and (Pv) diagrams.

** **mercury** is found to be most suitable in this respect.

Mercury (Hg)

- Mercury is characterized by :
at ($T = 604.6\text{ }^{\circ}\text{C}$) $\Rightarrow P_{\text{saturation}} \approx 24\text{ bar}$
- So at it's lowest saturation pressure gives temperature well above ($600\text{ }^{\circ}\text{C}$)
- or at $T = 600\text{ }^{\circ}\text{C} \rightarrow P_{\text{sat}} = \text{about } 23\text{ bar}$

conclusion

The usual temperature of heat rejection (or condensation) is about (25 – 30 °C).

At this temp., Hg is very disadvantageous as :

- i – its vapor pressure is extremely low .
- ii – it's specific volume is enormous.
ex. – from tables for Hg at lowest
T= 109.2 C
 $P_{\text{sat}} = 0.0006 \text{ bar}$
 $v_g = 259.6 \text{ m}^3 / \text{kg}$

and these figures are much worse if (30 C) temp. is considered.

For this reason :

1 – Hg is satisfactory at upper temperature limits

2 – steam is preferable at lower temperature limits

*At these operating conditions, combining both cycles into one “**BINARY VAPOR PLANT**”.*

Whereby

*** the heat required to evaporate the steam is obtained from the heat rejected to condense the mercury. ***

“”superheating, preheating, regeneration”” are all obtained by the combustion process of the main Hg boiler.

Cycle Analysis

As in simple steam cycle, the cycle thermodynamic analysis will be again based on the enthalpy drop across each component of the two cycles, so for example considering this cycle :

1- water cycle

Heat added $Q_{85} = h_5 - h_8$

Heat rejected $Q_{67} = h_6 - h_7$

Work done $W_{56} = h_5 - h_6$

2 - Mercury cycle

Heat added $Q_{21} = h_2 - h_1$

Heat rejected $Q_{34} = h_3 - h_4$

Work done $W_{23} = h_2 - h_3$

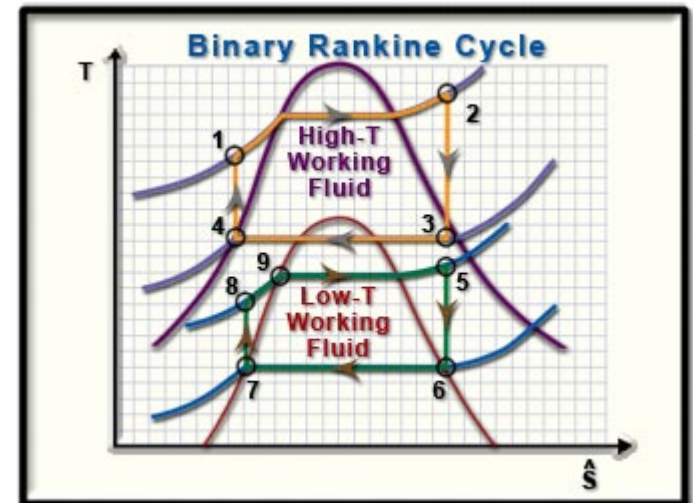
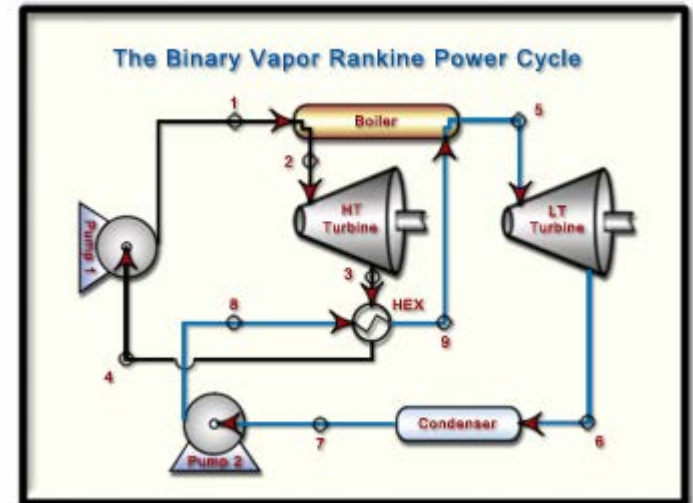
3 – combined cycle

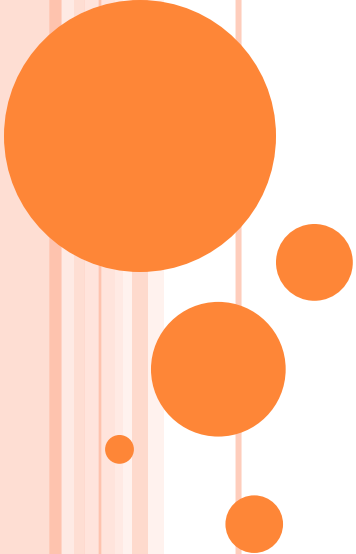
Cycle heat added $Q_T = Q_{21} = h_2 - h_1$

Cycle work done $W_T = W_{56} + W_{23}$

Cycle heat rejected $Q_R = Q_{67} = h_6 - h_7$

Cycle efficiency $\eta = W_T / Q_T$





CHAPTER TWO

STEAM POWER PLANT

2.02.5 – cogeneration

introduction

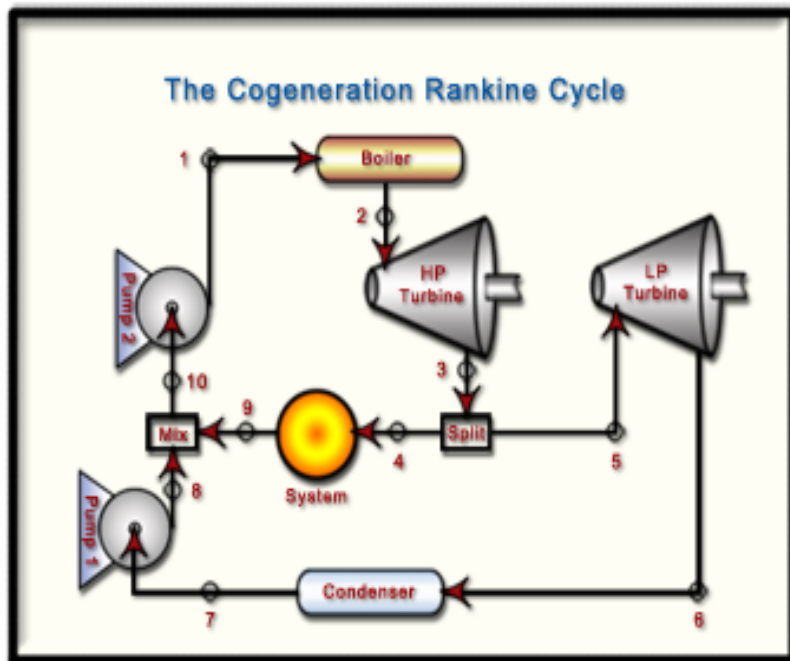
Cogeneration (*also known as combined heat and power, CHP*) is the use of a power station to simultaneously generate both

- 1 - work (generate electrical power) plus
- 2 - heat as high-quality or saturated steam at a moderately high (T & P) for some other use elsewhere .

Conventional power plants emit the heat created as a by-product (waste) of electricity generation into the natural environment through cooling towers, flue gas, or by other means, which in actual sense is a loss in percentage of fuel energy

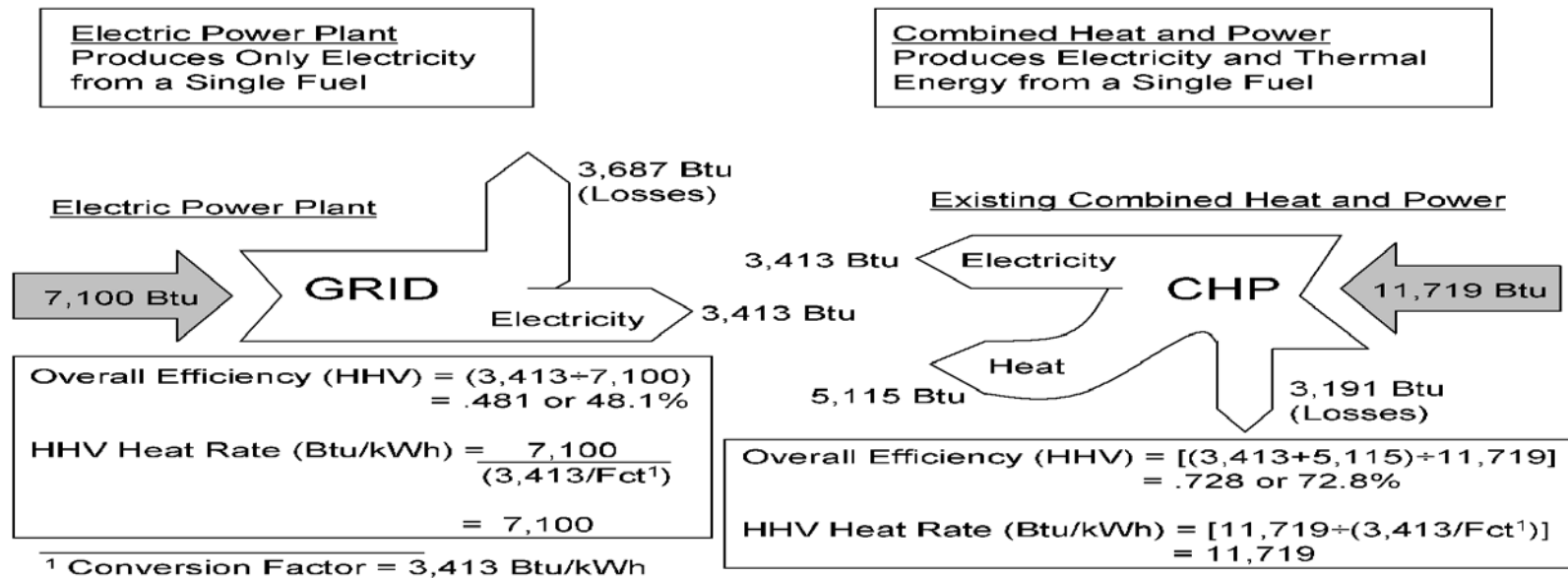
By contrast CHP captures the by-product heat for domestic or industrial heating purposes, either very close to the plant, or as hot water for district heating with temperatures ranging from approximately 80 to 130 °C. This is also called Combined Heat and Power District Heating or CHPDH. Small CHP plants are an example of decentralized energy

. It is considered as one of the most common forms of energy recycling



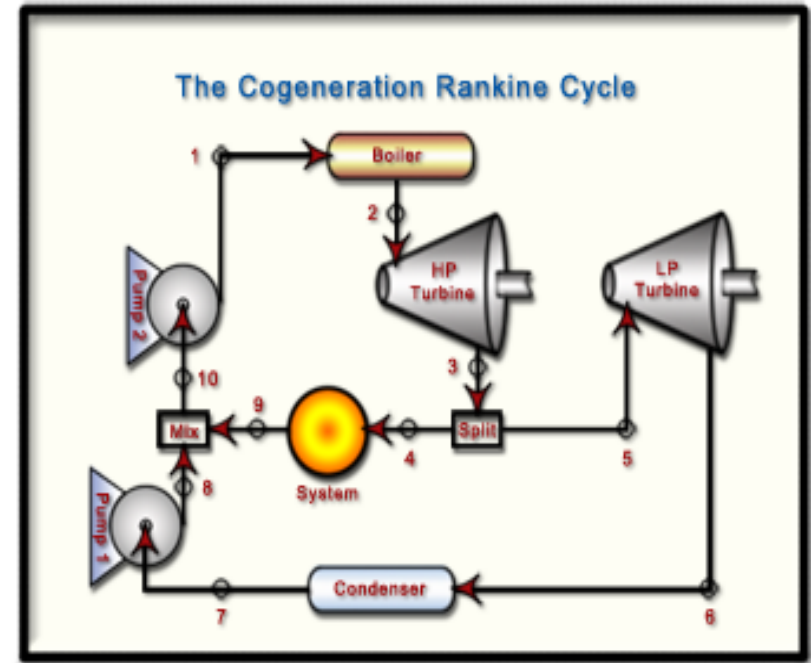
Cogeneration is a thermodynamically efficient use of fuel. In separate production of electricity some energy must be rejected as waste heat, but in cogeneration this thermal energy is put to good use. Thermal power plants (using fissile elements, coal, petroleum, or natural gas), and heat engines in general, do not convert all of their thermal energy into electricity. In most heat engines, a bit more than half is lost as excess heat. By capturing the excess heat, CHP uses heat that would be wasted in a conventional power plant, potentially reaching an efficiency of up to 89%, compared with 55% for the best conventional plants. This means that less fuel needs to be consumed to produce the same amount of useful energy.

Cogeneration (or CHP) versus Electric Power Plant Production



In the process flow diagram shown here, the high-quality effluent from the high pressure turbine, stream 3, is used as a heat source by the external system.

When stream 8 returns from the external system, it generally has a low quality or it can be a saturated liquid. Stream 8 is mixed with the subcooled liquid effluent from Pump #1 and then pumped up to the pressure of the boiler to complete the cycle.



- 1-2: Boiler - Heat added at constant pressure.
- 2-3: High-Pressure Turbine (HP) - Isentropic expansion.
- 3-4,5: Stream Splitter - A tee in a pipe.
- 4-9: External System - Uses heat.
- 5-6: Low-Pressure Turbine (LP) - Isentropic expansion.
- 6-7: Condenser - Heat rejected at constant pressure.
- 7-8: Pump #1- Isentropic compression
- 8,9-10: Mixing Chamber
- 10-1: Pump #2- Isentropic compression

- In power plants and chemical plants, there are many uses for steam :
 - * It can be used to provide heat for processes
 - * it can be used to drive pumps. In the process diagram above, we have lumped all of these external energy requirements into the circle labeled "System".
- Most of the uses for steam in this external system do not require valuable, expensive high-pressure steam.
- So, instead of sending the superheated steam in stream 2 to the external system, it is a more efficient use of energy to use stream 2 to produce work in the high-pressure turbine.
- Then, the needs of the external system can be met by diverting a portion of the cooler less valuable steam in stream 4 to the external system.
- When the steam returns from the external system it is usually a saturated liquid, but it is still at the discharge pressure of the high-pressure turbine.
- So, the condenser effluent must be pumped up to this pressure before the streams are combined. This helps avoid irreversibility's due to mixing streams at very different temperatures and pressures.
- The cycle is completed by pumping stream 10 back up to the pressure in the boiler.
- This cycle will be easier to understand when you see it on a TS Diagram.

USEFUL NOTES

- However, it is often not efficient to use the very valuable heat from the high temperature reservoir in the external process.
- It is often more efficient to use the heat from the high temperature reservoir to generate power and then use less valuable heat that is available at a lower temperature (stream 4) as the heat source for the external system.

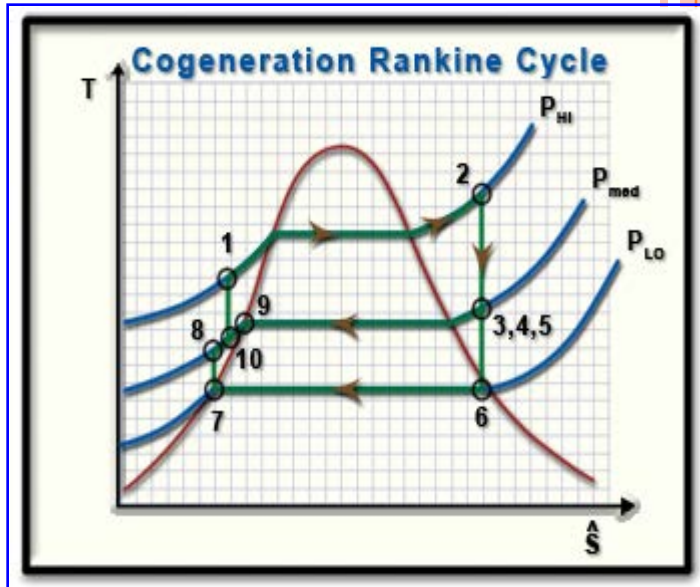
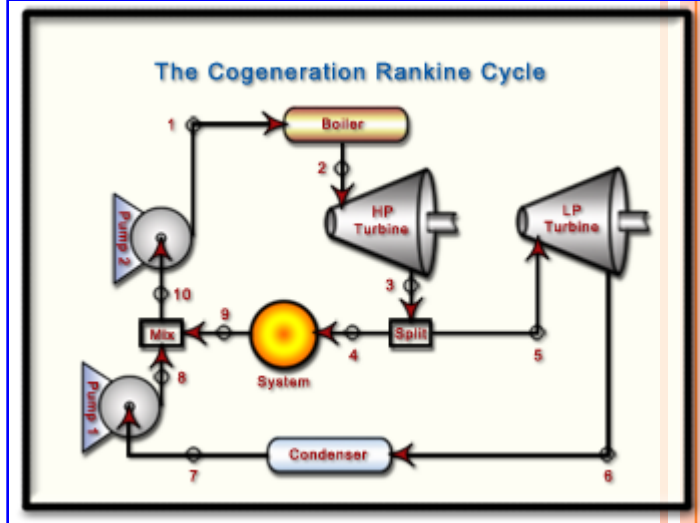
Cogeneration does not improve the **efficiency** of the **ideal Rankine Cycle**



TS Diagram for Cogeneration

Notice that streams 8 & 9 are mixed at the same pressure to form stream 10.

- This provides the fringe benefit of increasing the temperature of the boiler feed.
- This reduces the irreversibility of the heat transfer in the boiler just as in the regenerative Rankine Cycle.
- cogeneration does not improve the efficiency of the power cycle, but it can improve the efficiency of an entire plant by reducing the lost work in the external system.
- The key to this improvement is providing steam that is just hot enough to do the job in the external system and not wasting hotter more valuable high-pressure steam.



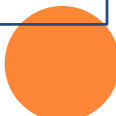
Application examples

A car engine becomes a CHP plant in winter, when the reject heat is used for warming the interior of the vehicle.

district heating systems of cities, hospitals, oil refineries, paper mills, wastewater treatment plants, thermal enhanced oil recovery wells and industrial plants with large heating needs.

Thermally enhanced oil recovery (TEOR) plants often produce a substantial amount of excess electricity. After generating electricity, these plants pump leftover steam into heavy oil wells so that the oil will flow more easily, increasing production.

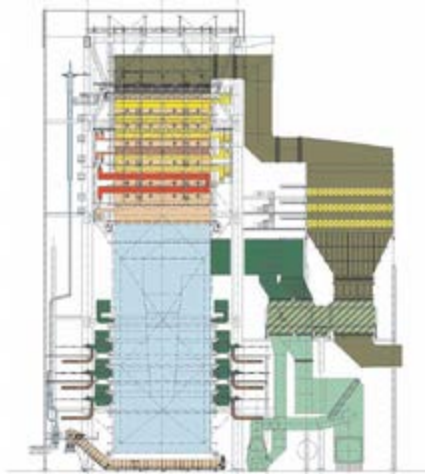
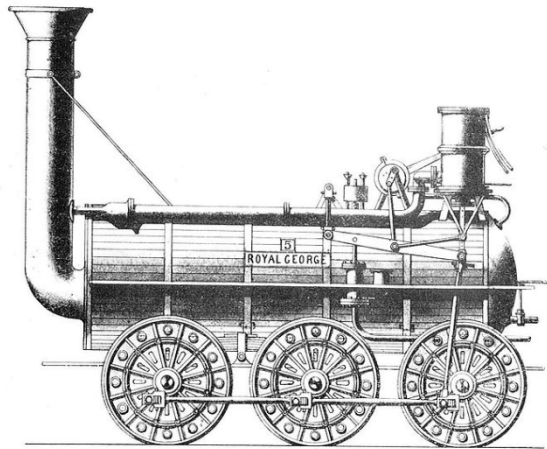
In the United States, Con Edison company distributes 30 billion pounds of 180 °C steam each year through its seven cogeneration plants to 100,000 buildings in Manhattan—the biggest steam district in the world. The peak delivery is 10 million pounds per hour (corresponding to approx. 2.5 GW) This steam distribution system is the reason for the steaming manholes often seen in "gritty" New York movies.



Chapter two

STEAM POWER PLANT

(steam generator) 2.03 - Boiler
2.03.1 - descriptive



Watertube Boiler D-Type



Watertube Boiler "A Type"



Watertube Boiler "O Type"



Miura Watertube Boiler

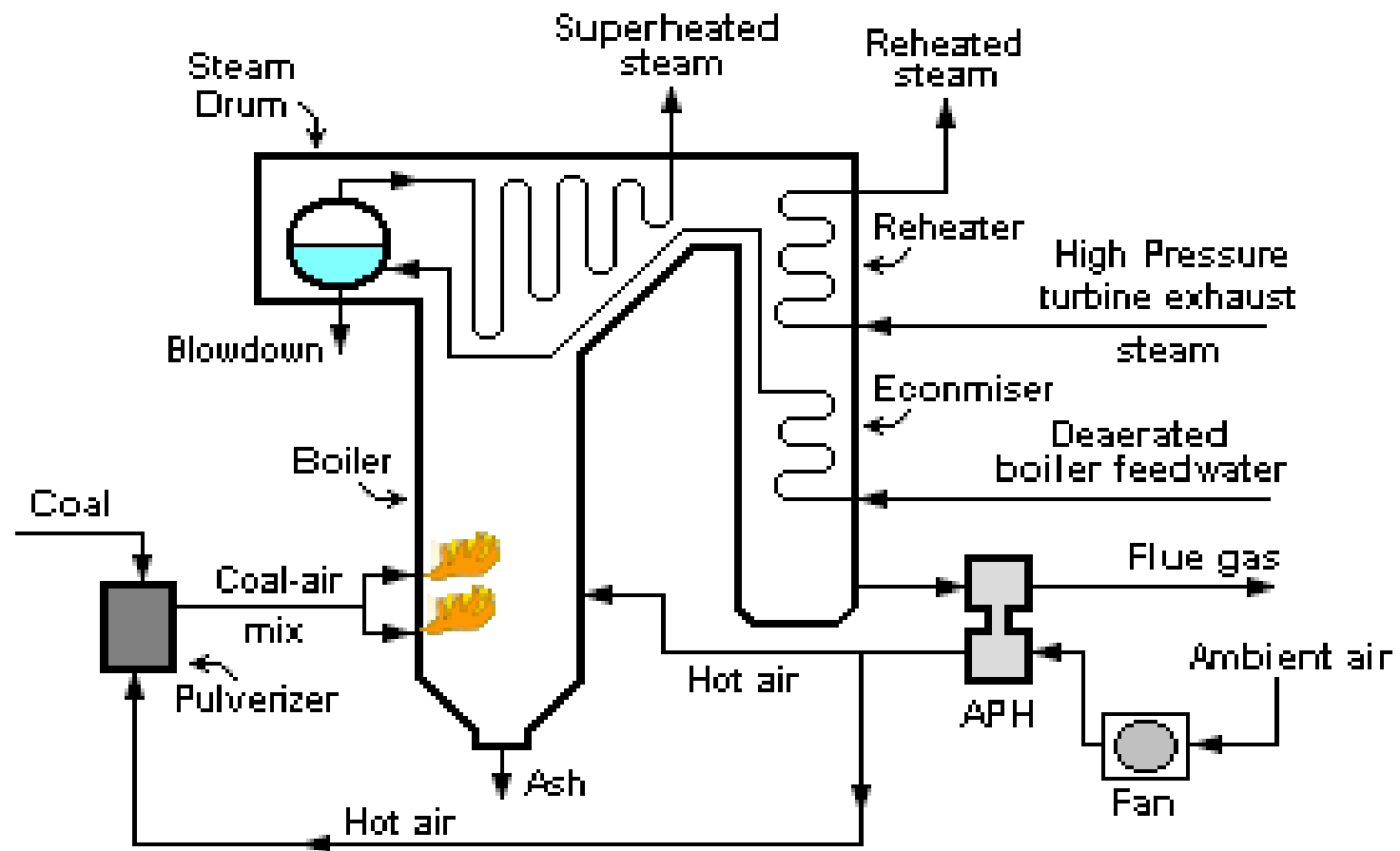




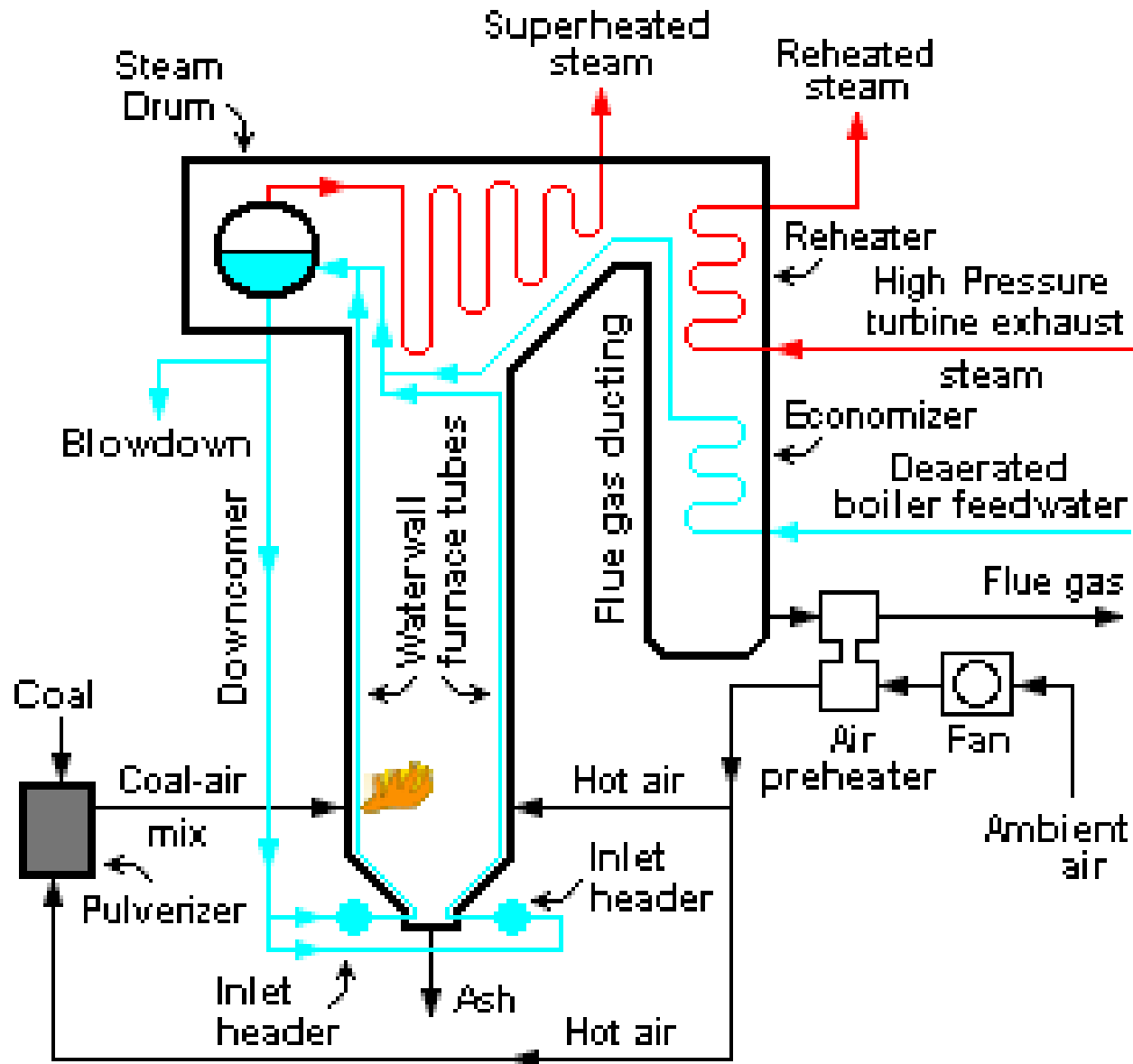
Boiler

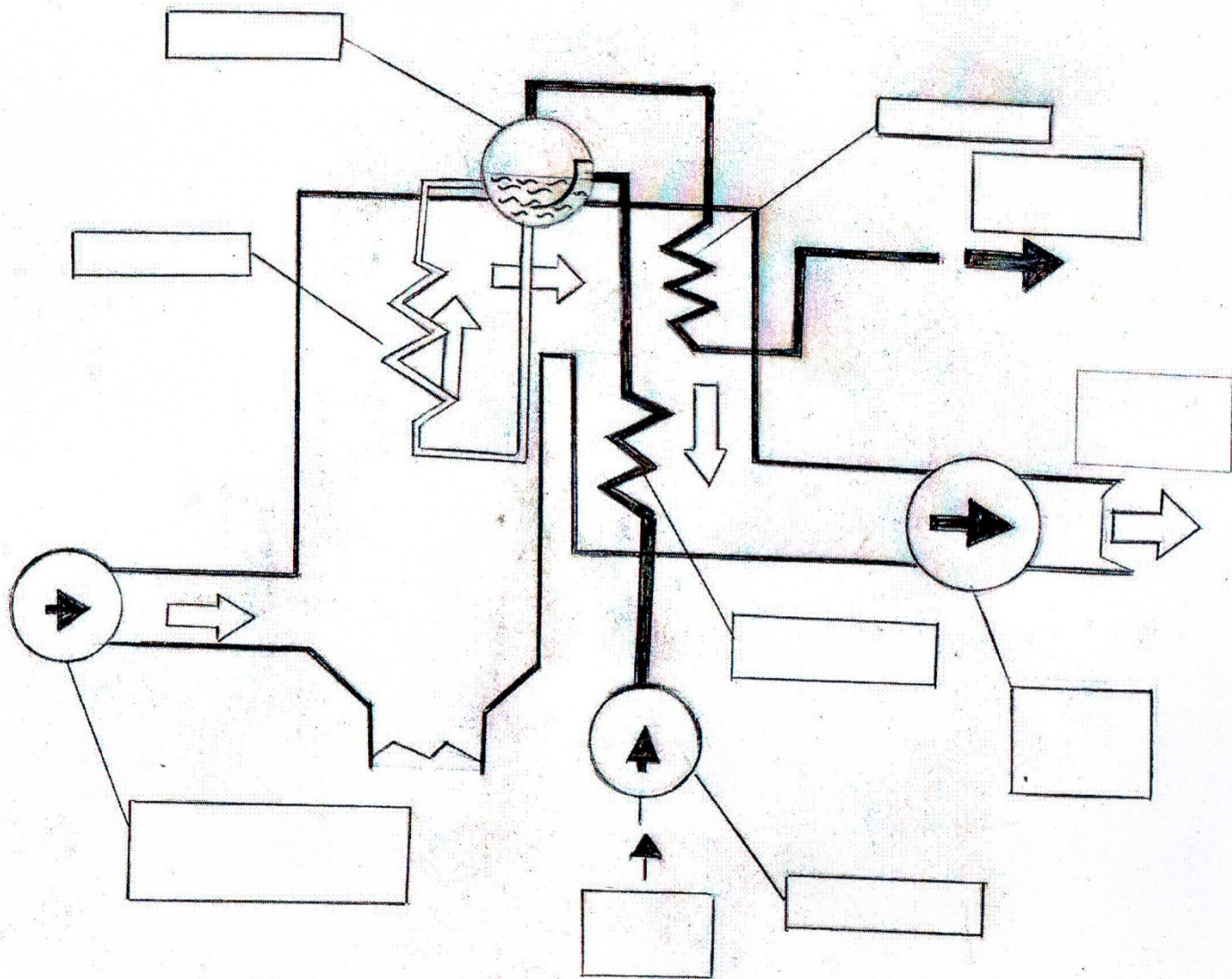
steam generator

- A **boiler** or **steam generator** is a device used to create steam by applying heat energy to water. Although the definitions are somewhat flexible, it can be said that older steam generators were commonly termed *boilers* and worked at low to medium pressure (0.069-20.684) bar
- but at pressures above this, it is more usual to speak of a *steam generator*



Note: APH is the air preheater





Basics.

- Volume of one unit mass of steam is thousand times that of water, When water is converted to steam in a closed vessel the pressure will increase. Boiler uses this principle to produce high pressure steam.
- Conversion of Water to Steam evolves in three stages.
- Heating the water from cold condition to boiling point or saturation temperature – sensible heat addition.
- Water boils at saturation temperature to produce steam - Latent heat addition.
- Heating steam from saturation temperature to higher temperature called Superheating to increase the power plant output and efficiency.

Terminology

A boiler is a closed vessel in which water is heated, a steam is generated, or steam is superheated (or any combination of these) under pressure or vacuum by the application of heat from combustible fuels, electricity, or nuclear energy. Boilers are generally subdivided into four classic types, residential, commercial, industrial, and utility:

1 – Residential boilers produce low-pressure steam or hot water primarily for heating application in private heating.

2 – Commercial boilers produce steam or hot water primarily for heating application in commercial use, with incidental use in process operation.

3 – industrial boilers steam or hot water primarily for process application with incidental use as heating.

4 – utility boilers produce steam primarily for the production of electricity.

Boiler components

To understand the operation of a boiler, it is necessary to observe what happens from input to output of the unit. Several cycles are involved in the complete operation of the unit:

1. The heat cycle
2. The water and steam cycle
3. The boiler water circulation cycle.

These cycles all interact to produce the output of the boiler.

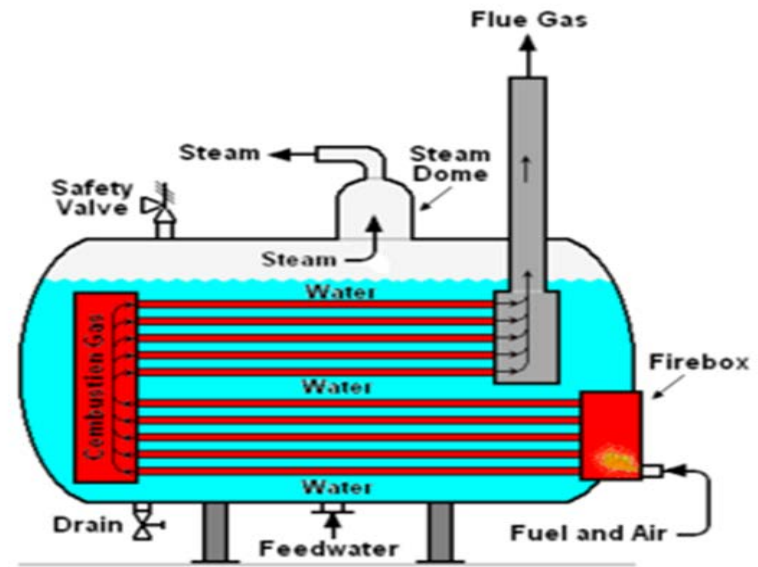
Fuel and water are brought to the unit; water is heated to its final pre-designated condition (water and/or steam) and transported to the point of its end use.

When the heat has been taken out of the water, the remaining steam and water mixture (or condensate), if usable is returned to the unit and recycled.

The major components generally incorporated in an industrial or utility boilers are :

1. Furnace
2. Boiler section
3. Super-heater
4. Air pre-heater
5. economizer

- A boiler incorporates a firebox or furnace in order to burn the fuel and generate heat; the heat is initially transferred to water to make steam; this produces saturated steam at ebullition temperature saturated steam which can vary according to the pressure above the boiling water. The higher the furnace temperature, the faster the steam production. The saturated steam thus produced can then either be used immediately to produce power via a turbine and alternator, or else may be further [superheated](#) to a higher temperature; this notably reduces suspended water content making a given volume of steam produce more work and creates a greater temperature gradient in order to counter tendency to condensation due to pressure and heat drop



resulting from work plus contact with the cooler walls of the steam passages and cylinders.

Any remaining heat in the combustion gases can then either be evacuated or made to pass through an [economizer](#), the role of which is to warm the feed water before it reaches the boiler.

Classification of Steam generators

- From 200 B.C. to date, many developments have taken place that today allow us to classify steam boilers in different ways. Hence steam generating boilers can be classified under various categories. The main purpose of steam boilers is to generate steam, and so the way in which the steam is generated and consumed forms the major category. The major two groups of boiler application are Industrial steam generators and power generation boilers. Boilers are also classified as fire tube and water tube boilers. In general boilers are classified according to the following categories :

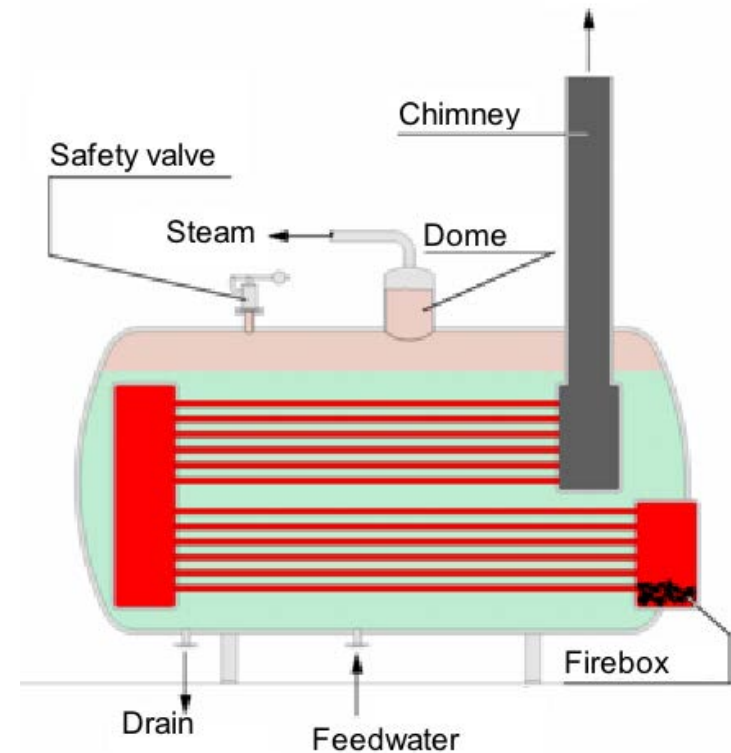
Classification categories

- 1 – flow of water and hot gas
- 2 – type of firing
- 3 – types of fuel used
- 4 – construction arrangement
- 5 - furnace position
- 6 – principle axis
- 7 – water circulation
- 8 – steam pressure

1 a - Fire tube boilers

- *Fire tube boilers have almost become extinct; however this can be classified as :*
- Locomotive boilers, which ruled rail transportation before diesel and electric engine came.
- Industrial boilers, mainly used for green projects where initial steam is required
- Domestic use boilers

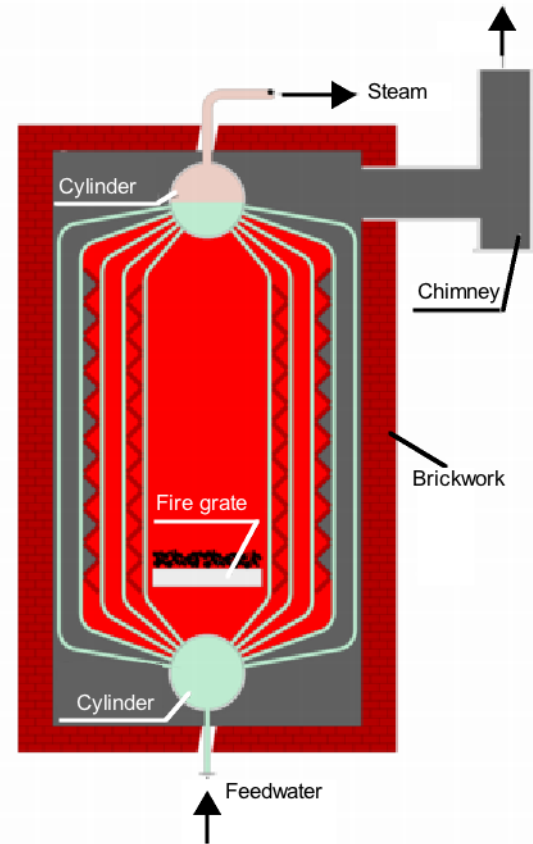
Fire-tube [boiler](#). Here, water partially fills a boiler barrel with a small volume left above to accommodate the steam (*steam space*). This is the type of boiler used in nearly all steam locomotives. The heat source is inside a furnace or *firebox* that has to be kept permanently surrounded by the water in order to maintain the temperature of the *heating surface* just below [boiling point](#). The furnace can be situated at one end of a fire-tube which lengthens the path of the hot gases, thus augmenting the heating surface which can be further increased by making the gases reverse direction through a second parallel tube or a bundle of multiple tubes (two-pass or return flue boiler); alternatively the gases may be taken along the sides and then beneath the boiler through flues (3-pass boiler). In the case of a locomotive-type boiler, a boiler barrel extends from the firebox and the hot gases pass through a bundle of fire tubes inside the barrel which greatly increase the heating surface compared to a single tube and further improve heat transfer. Fire-tube boilers usually have a comparatively low rate of steam production, but high steam storage capacity. Fire-tube boilers mostly burn solid fuels, but are readily adaptable to those of the liquid or gas variety.

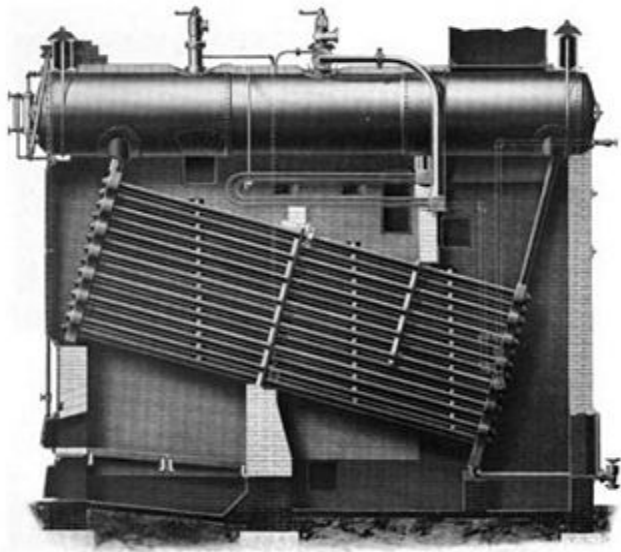


1 b - Water tube boilers

- ***Water tube boilers took over when size and capacity increased. This can be classified depending on type of circulation used to generate steam as***
- **Natural circulation boiler**
- **Forced circulation boilers**
- **Super critical pressure boilers or zero circulation boilers**

Water-tube boiler: In this type, the water tubes are arranged inside a furnace in a number of possible configurations: often the water tubes connect large drums, the lower ones containing water and the upper ones, steam and water; in other cases, such as a monotube boiler, water is circulated by a pump through a succession of coils. This type generally gives high steam production rates, but less storage capacity than the above. Water tube boilers can be designed to exploit any heat source and are generally preferred in high pressure applications since the high pressure water/steam is contained within small diameter pipes which can withstand the pressure with a thinner wall.

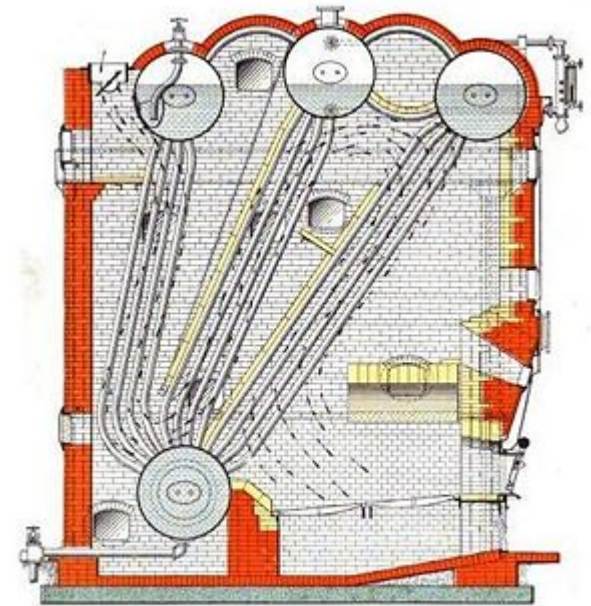




Babcock and Wilcox Water-tube Boiler with Longitudinal Steam Drum

The steam drum can be arranged either parallel to the tubes (as shown in Fig) or transverse to the tubes, in which case the boiler was referred to as being a "cross drum" rather than a "longitudinal drum" boiler. Cross drum boilers could accommodate more tubes than longitudinal drum boilers and they were designed to generate steam pressures of up to about 100 bar and at rates ranging up to about 225,000 kg/hour.

Water-tube boilers with longitudinal steam drums, as in Fig above were developed to allow increases in generated steam pressure and increased capacity. The water-tube boilers, in which water flowed through inclined tubes and the combustion product gases flowed outside the tubes, put the desired higher steam pressures in the small diameter tubes which could withstand the tensile stress of higher pressures without requiring excessively thick tube walls.



Stirling Water-tube Boiler with Four Cross-Drums

The red, yellow and blue sections are red brick, fire brick and concrete

The three sets of bent tubes, as shown in above Fig, each represent a bank of tubes extending from the front of the steam drums back to the rear of the drums. Thus, the longer the steam drums, the more tubes were available and the more [heat transfer](#) surface was available. The tubes were bent slightly so that they entered and exited the steam drums radially.

The major shortcoming of fire-tube boilers is that the water and steam are contained within the outer cylindrical shell and that shell is subject to size and pressure limitations. The **tensile stress** on the cylindrical shell walls is a function of the shell **diameter** and the internal steam pressure:

$$\sigma = \frac{p d}{2 t}$$

where σ is the tensile stress (hoop stress) in **Pa**, p is the internal **gauge pressure** in Pa, d is the internal diameter of the cylindrical shell in **m** and t is the thickness of the cylindrical shell wall in m.

The ever-growing need for increased quantities of steam at higher and higher pressures could not be provided by fire-tube boilers because, as can be seen in the above equation, both higher pressures and larger diameter shells led to prohibitively thicker and more expensive shells.

The large steam generators used in modern power plants to generate electricity are almost entirely some type of water-tube design, owing to their ability to operate at higher pressures.

2 - type of firing

- *Depending on type of firing adopted in boilers they can be classified as*
- **Stoker fired**
- **Pulverized coal fired**
- **Down shot fired**
- **Fluidized bed boilers**
- **Cyclone fired**
- **Chemical recovery boilers**
- **Incinerators**
- Of these the stokers which were predominantly used in early days of high pressure high capacity boilers are being replaced by pulverized coal fired boilers and fluidized bed boilers. Stoker boilers are still designed and used in few applications like sugar industries, etc.

3 - type of fuel used

- *Boilers can be classified based on the type of fuel used as*
- Coal fired boilers
- Oil fired boilers
- Gas fired boilers
- Multi-fuel fired
- Industrial waste fired boilers
- Biomass fired boilers

4 - types of arrangement

- **Various types of arrangement** are used by designers in designing the boiler for meeting the end requirement. Hence boilers are classified based on the arrangement as
- **Top supported boilers**
- **Bottom supported**
- **Package boilers**
- **Field erected boilers**
- **Drum type boilers**
 - Single drum
 - Bi drum
 - Three drums, but these are presently out of use
- **Tower type or single pass**
- **Close coupled**
- **Two pass boilers**
- Boilers therefore can be classified based on firing type, fuel used, construction type, circulation type, firing system design nature, and nature of steam application. Today's steam generating systems owe their dependability and safety to more than 125 years of experience in the design, fabrication, and operation of water tube boilers.

Other classification categories

5 - furnace position

i-internally fired

ii-externally fired

In the internally fired the grate combustion chamber are enclosed within the boiler shell , whereas in the case of externally fired boilers and furnace and grate are separated from the boiler shell. However, a **furnace** is a device used for [heating](#), or in this respect it refer to a direct fired heater, used in industrial boiler application

Modern Furnace components

The furnace components can be divided into three categories.

1. The burners, heat exchanger, draft inducer, and venting.
2. The controls and safety devices.
3. The blower and air movement .

- 6 – position of principle axis

- i – vertical
- ii – horizontal
- iii – inclined

- 7 – application

- i – stationary
- ii – mobile (marine , locomotive)

8 – steam pressure

- general classification in terms of pressure is
 - i – low pressure
 - ii – medium pressure
 - iii – high pressure
- However for electricity generation, a power plant steam generator better be classified as either :
 1. a *subcritical* (below 221 bar) or
 2. a *supercritical* (above 221 bar) steam generator.
- Figure A is a photo that shows the magnitude of a large modern power plant that generates subcritical steam from combustion of a fuel and Figure B is a photo that shows the magnitude of a large supercritical steam power plant.

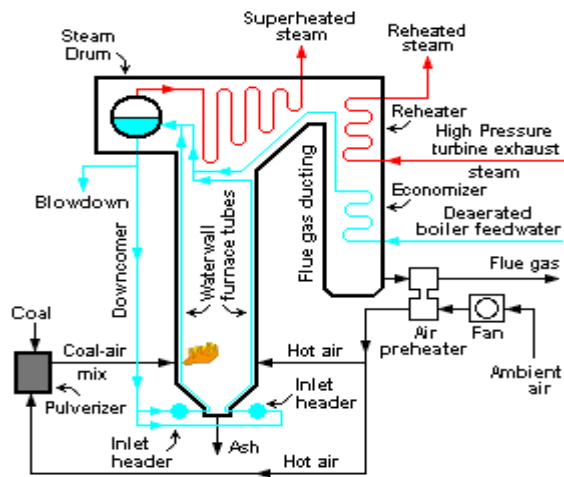


Figure A: Large, coal-fired subcritical steam generator in a power plant.



Figure B: Two 750 MW oil and gas-fired, supercritical steam to electric power plants

The output superheated steam from subcritical steam generators, in power plants using fuel combustion, usually range in pressure from *130 to 190 bar, in temperature from 540 to 560 °C and at steam rates ranging from about 400,000 to about 5,000,000 kg/hour*.

The adjacent Figure A provides a schematic diagram of a typical electric power plant using fuel combustion to generate subcritical steam and

Figure 5B depicts the physical appearance of such power plants. The overall height of such steam generators ranges up to about 70 metres.

9 – water circulation

- The flow from the drum through the evaporator back to the drum, may be either :
- i -forced circulation
- ii - natural circulation
- A **forced circulation** system uses a pump to maintain circulation in all the tubes of the evaporator tube bundle
- for **natural, "thermosyphon", circulation** . This means the water and steam/water circuits are arranged so that the two phase mixture in the steam generating tubes rises to the steam drum by thermal lift of differential density and is replaced by water from the drum by gravity flow.

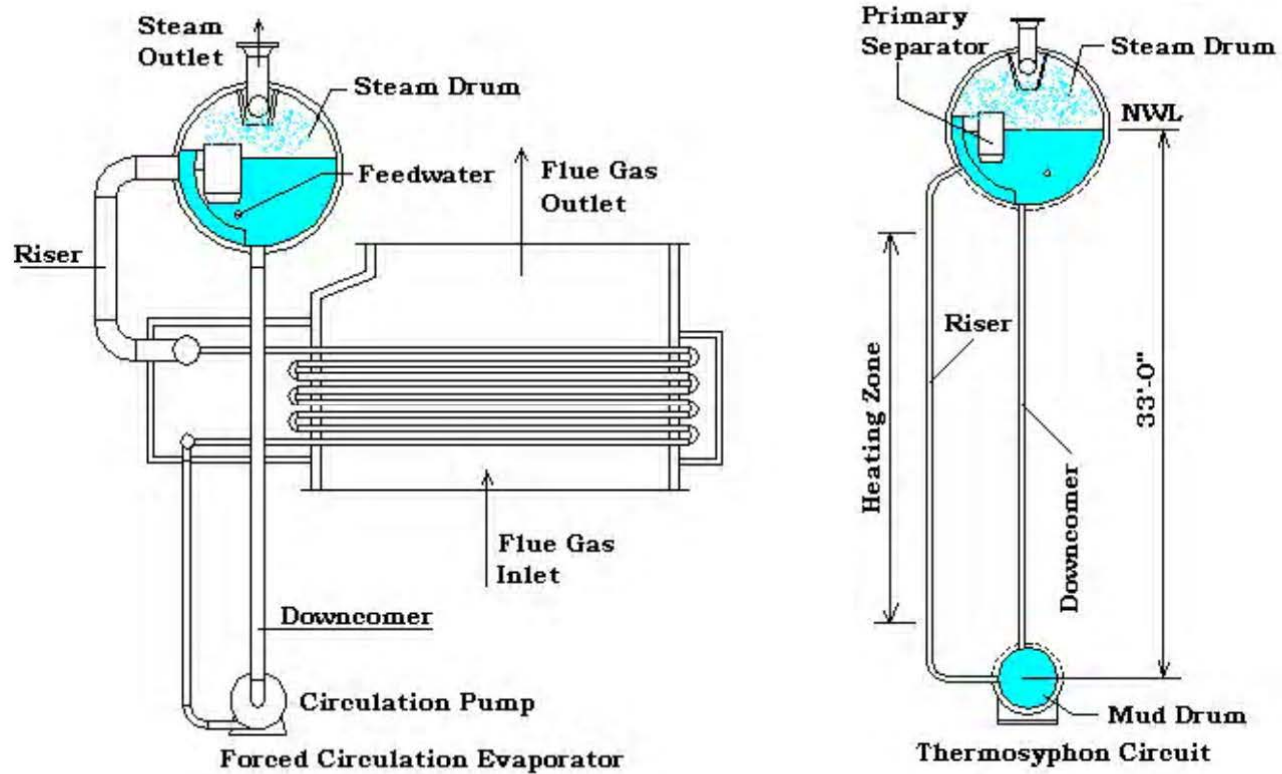


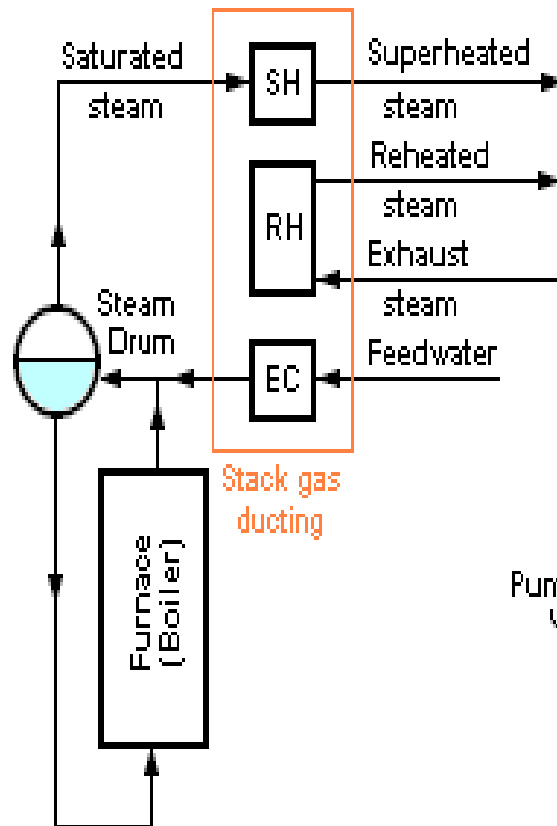
Figure 69 *Steam drum system in an HRSG. Left: forced circulation. Right: natural circulation*

There are three configurations for such steam generators:

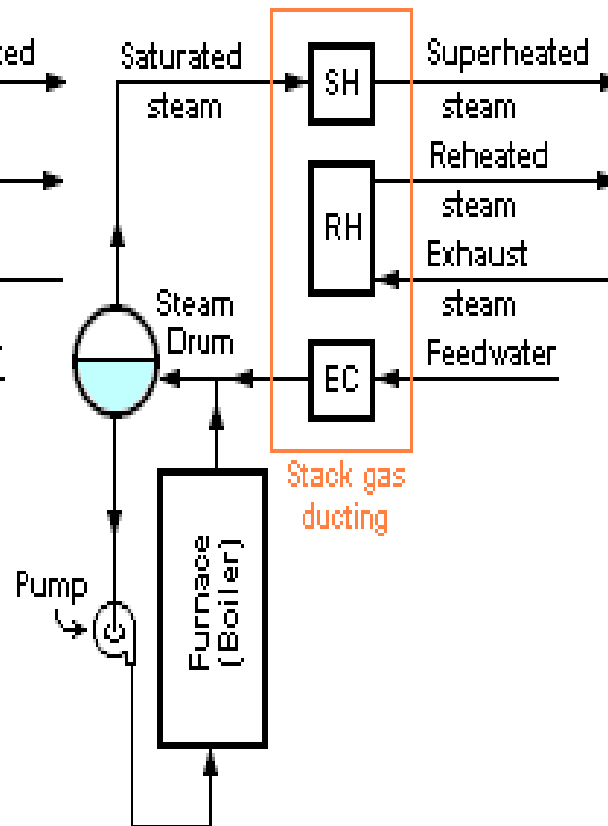
1. Natural circulation in which liquid water flows downward from the steam drum via the downcomer (see Figure 5A) and a mixture of steam and water returns to the steam drum by flowing upward via the tubes embedded in the furnace wall. The difference in density between the downward flowing liquid water and the upward flowing mixture of steam and liquid provides sufficient driving force to induce the circulating flow.
2. Forced circulation in which a pump in the downcomer provides additional driving force for the circulating flow. The assistance of a pump is usually provided when generating steam at above about 170 bar because, at pressures above 170 bar, the density difference between the downcomer liquid and the liquid-steam mixture in the furnace wall tubes is reduced sufficiently to limit the circulating flow rate.
3. A once-through system in which no steam drum is provided and the boiler feedwater goes through the economizer, the furnace wall tubes and the superheater section in one continuous pass and there is no recirculation. In essence, the feedwater pump supplies the motive force for the flow through the system.

Figure 6 below schematically depicts the three configurations:

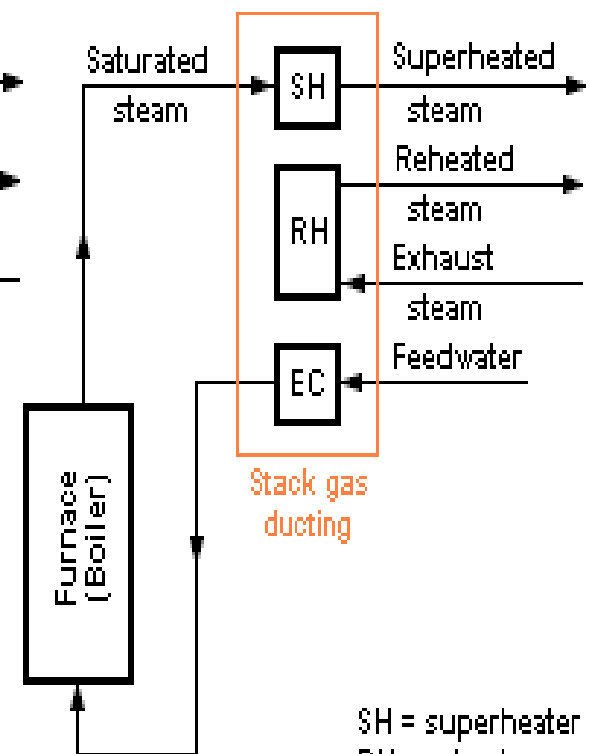
Natural Circulation



Forced Circulation



Once-Through



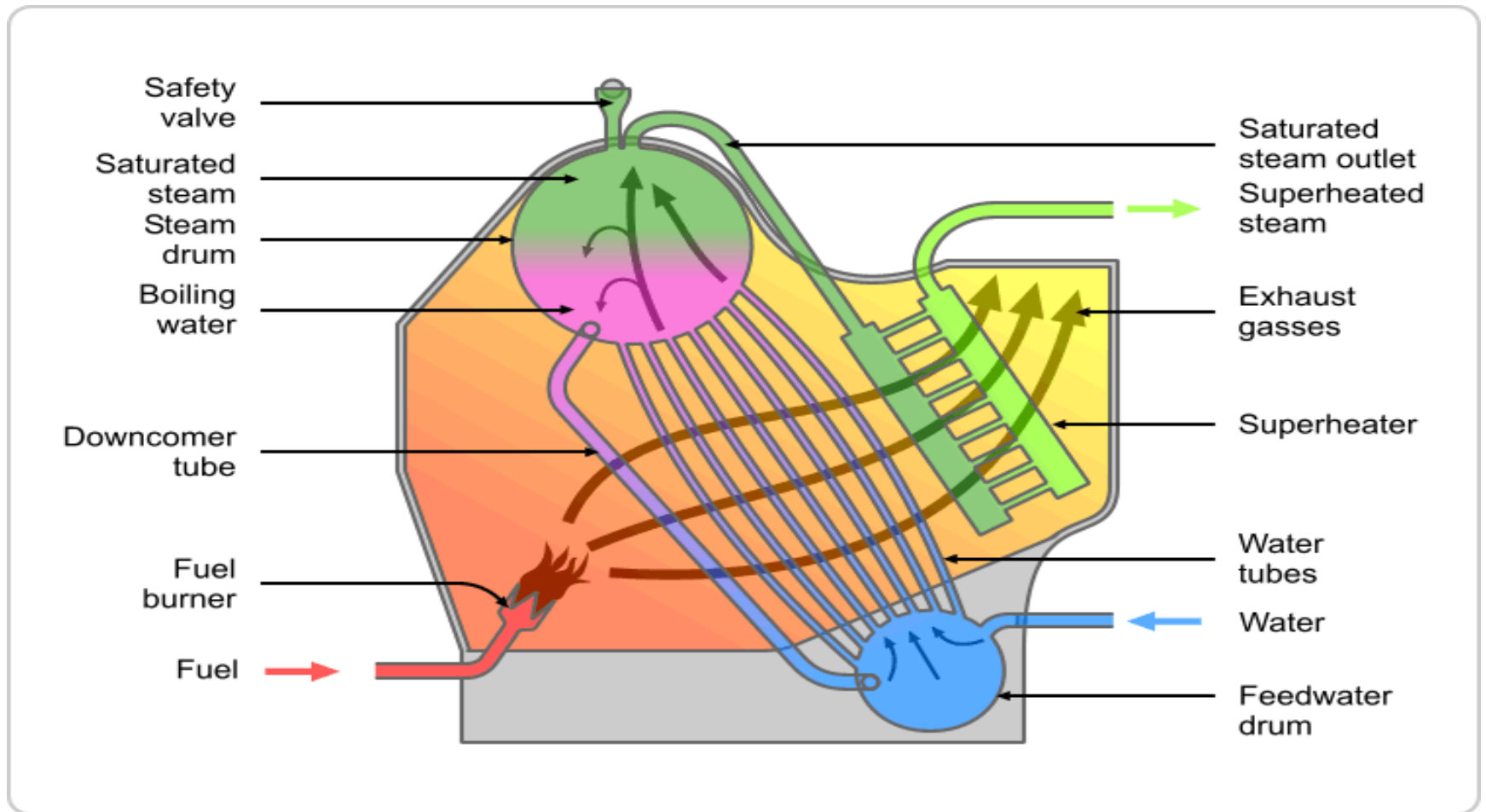
SH = superheater
RH = reheater
EC = economizer

Three Configurations for Subcritical Power Plant steam Generators

Steam drum

- A **steam drum** is a standard feature of a water-tube boiler. It is a reservoir of water/steam at the top end of the water tubes. The drum stores the steam generated in the water tubes and acts as a phase-separator for the steam/water mixture. The difference in densities between hot and cold water helps in the accumulation of the "hotter"-water/and saturated-steam into the steam-drum.

water tube boiler drum

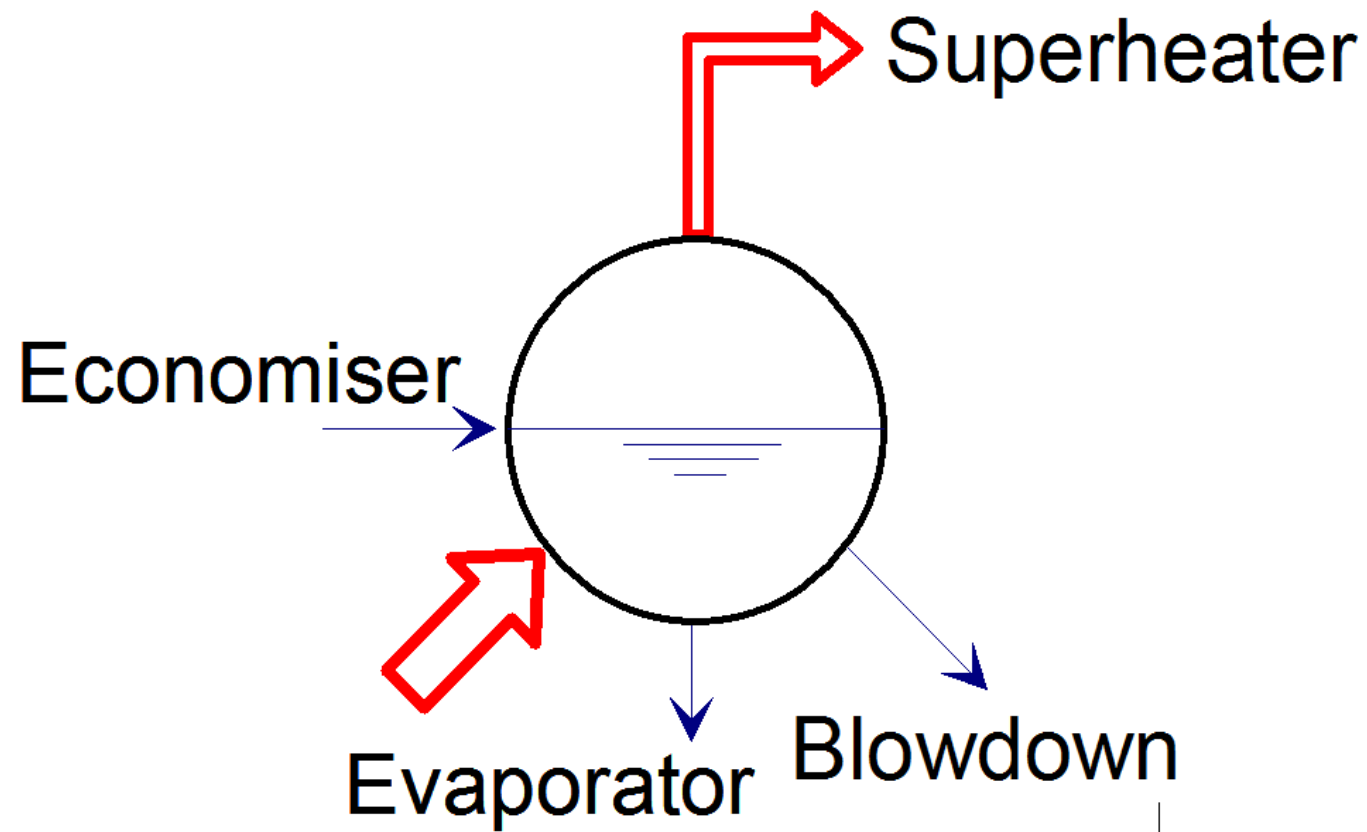


- Made from high Carbon Steel with high tensile strength and its working involves temperatures around 390°C and pressures well above 30 psi (2.1 MPa). The separated steam is drawn out from the top section of the drum and distributed for process. Further heating of the saturated steam will make superheated steam normally used to drive a [steam turbine](#). Saturated steam is drawn off the top of the drum and re-enters the furnace in through a [superheater](#). The steam and water mixture enters the steam drum through riser tubes, drum internals consisting of demister separate the water droplets from the steam producing dry steam. The saturated water at the bottom of the steam drum flows down through the downcomer pipe, normally unheated, to headers and water drum. Its accessories include a safety valve, water-level indicator and level controller. Feed-water of boiler is also fed to the steam drum through a feed pipe extending inside the drum, along the length of the steam drum.

A drum or steam drum connects the economizer, evaporator and the superheater in an HRSG. There is a drum for every pressure level in the HRSG (not for reheating, if regarding that as a pressure level). The cross-section of the drum is circular, with a diameter in the range 1-2m. The length depends on the size of the plant, may be up to 15 m. The drum is filled about 50% with liquid water, where the water at the surface is at the boiling point. The hot water from the economizer is entering the drum and is distributed in the water volume. A sketch of a drum is given in Figure 68. The drum is a pressure vessel with two main functions: Separating liquid water and saturated steam Remove impurities in the feed water

From the drum, water is led to the evaporator. Back from the evaporator a two-phase mixture is returned to the drum, above the water volume. This two-phase mixture goes normally through hydro cyclones, where the steam and the liquid water are separated. The steam leaves at the top of the drum for the superheater, while the liquid water returns down into the water volume. The steam/liquid water in the drum is at the saturation state, ensured by heat and mass transfer between the saturated steam in the upper half of the drum, and the liquid water at the boiling point in the lower half of the drum.

A steam drum is used without or in the company of a **mud-drum/feed water drum** which is located at a lower level. A boiler with both steam drum and mud/water drum is called a bi-drum boiler and a boiler with only a steam drum is called a mono-drum boiler. The bi-drum boiler construction is normally intended for low pressure-rating boiler while the mono-drum is mostly designed for higher pressure-rating.



The concepts of boiler operation & rating

1. The concept of “boiler horsepower” (bhp)

One *bhp* is the evaporation of 15.648 kg of water per hour from a temperature of 100°C into dry saturated steam at the same temperature. Equivalent to 35.291 MJ/h.

A boiler rated 1,000 bhp has therefore enough heating surface to adsorb [1,000 * 35.291 = 35,291 MJ/h] of energy to the steam-water circuit.

A boiler rated at 30 bar and 1,000 bhp will not have a guaranteed generation of [1,000 * 34.5 / 2,204.75 = 15.6 tons] of steam per hour because as stated, the term *bhp* refers to heating water from and at 100 °C.

Boiler horsepower ratings are rapidly phased out and rarely found in new boiler installations, except for American boilers.

2. The concept of “tons of steam/hour”

This term is the most informative and easiest to understand if it refers to steam properties the boiler is designed for.

3. The concept of “heat output”

It means the adsorbed heat in the steam-water circuit at specific operating conditions.

1 BTU = 1,054.35 Joule and

1 MW = 3,600 MJ/h

In practice the rated or nominal heat output is the continuous maximum heat adsorption capacity of the boiler. To what extent all this heat is used to generate steam depends on the operation.

4. Pressure ratings

On the name plate of boilers you may find its pressure rating in either *bar*, *kPa*, or *psi*. The pressure rating refers to the highest boiler drum pressure (= steam pressure) the boiler should be operated. The conversion factors are

$$\begin{array}{lll} 1 \text{ psi} & = 6,894.8 \text{ Pa} & = 6.8948 \text{ kPa} \\ 1 \text{ bar} & = 100,000 \text{ Pa} & = 100 \text{ kPa} \end{array}$$

The above units *bar*, *kPa*, and *psi* are also found on steam pressure gages. In addition the unit *kp/cm²* (or *kg/cm²*) is occasionally found on gages.

$$1 \text{ kp/cm}^2 = 0.9807 \text{ bar}$$

$$1 \text{ kg/cm}^2 = 1 \text{ atm}$$

Definition of parameters of boiler operation

Adapting a few terms common in the operation of power plants to get a better overview about existing problems with a boiler that are hidden to an occasional visitor.

The *Dependable Capacity* of a boiler is the maximum heat output under specific conditions for a given time interval (day, month, year).

The **Average Load** is defined as

$$\text{Average load} = \frac{\text{Actual heat output}}{\text{Operating hours}}$$

The *Average Load* shows how much of the *Dependable Capacity* is being utilized by the boiler. [*Average Load = Dependable Capacity*] means 100 % utilization.

The **Availability** is defined as

$$\text{Availability} = \left(1 - \frac{\text{FOH} + \text{MOH} + \text{POH}}{\text{Period hours}} \right) \cdot 100$$

The higher the percent Availability, the more the boiler is available to supply steam, where

FOH = Forced outage hours (boiler or downstream failures)

MOH = Maintenance outage hours (scheduled repair)

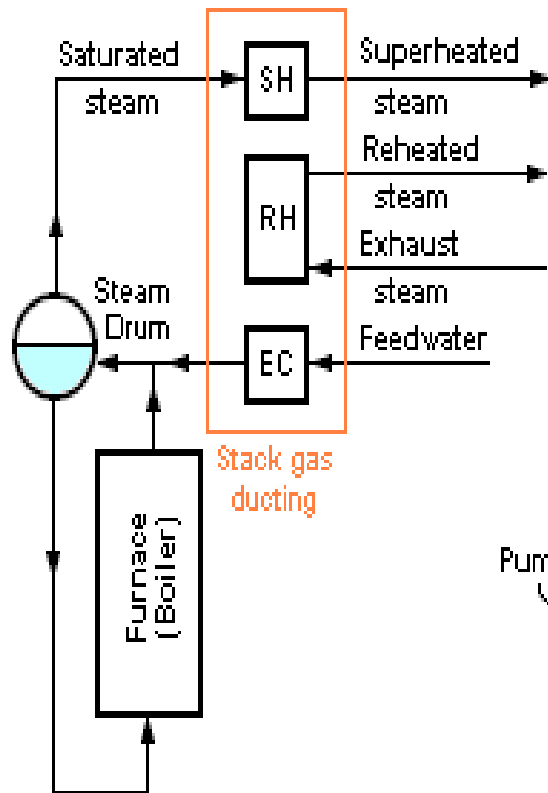
POH = Planned outage hours (non operation due to events such as Sundays, two shifts, etc.)

The **Capacity Factor** is defined as

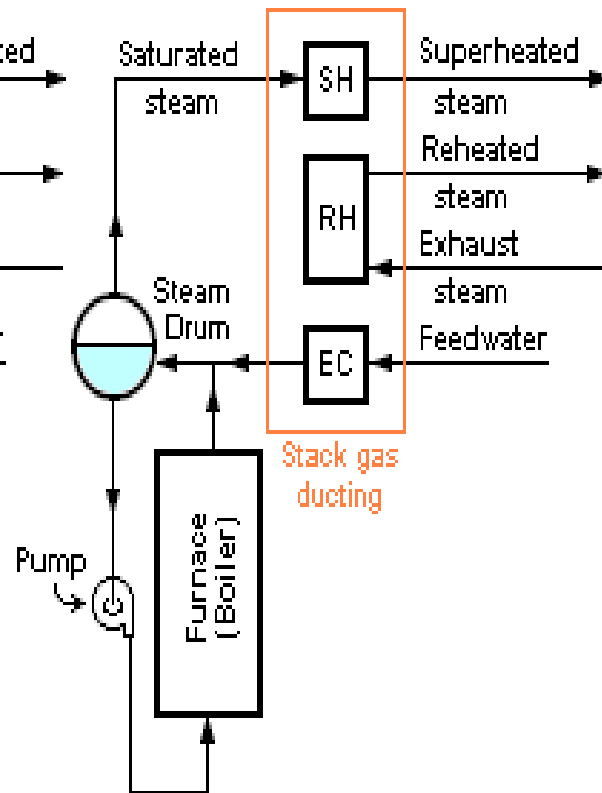
$$\text{Capacity Factor} = \frac{\text{Actual heat output}}{\text{Rated heat output} \cdot \text{Period hours}} \cdot 100$$

The higher the Capacity Factor, the longer the unit is being used. Period hours may refer to any time frame from one day, a week, months, a year or time since commissioning of the boiler. For accounting purposes we assume 8,760 hours/year and 365 days/year.

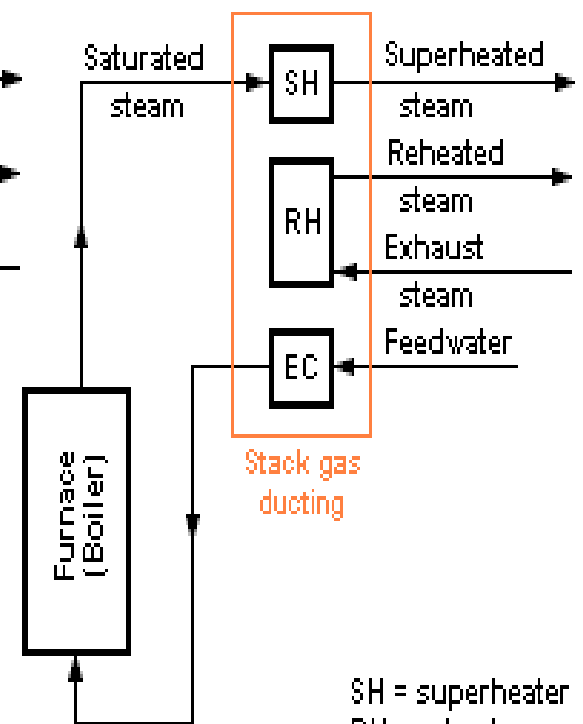
Natural Circulation



Forced Circulation



Once-Through



SH = superheater
RH = reheater
EC = economizer

Three Configurations for Subcritical Power Plant steam Generators

Chapter two

steam power plant

2.03 – steam generator

2.03.2 - analysis

Evaporative capacity

- The evaporative capacity of a boiler may be expressed in terms of :
 1. kg steam / hr
 2. kg of steam / hr / m² of heating surface
 3. kg of steam / kg of fuel

Equivalent evaporation

- Evaporative capacity of kg/hr does not give fair means of performance comparison between different boilers operating at different conditions.
- So, standard conditions adopted for such purpose are :
 - *“ temperature of feed water @ 100 °C converted to dry saturated steam @ 100 °C “ .*
 - *Accordingly, 1 kg of water @ 100 °C necessitates (2257) kJ to get converted to dry saturated steam @ 100 °C.*
 - *Equivalent evaporation is defined as “ the amount of water evaporated from water @100°C to dry saturated steam @ 100°C*

Let

m_s : kg steam /hr @ P & T

h : enthalpy of steam per kg under the generating conditions
and since

$$h = h_f + h_{fg} \quad \text{dry saturated steam @P}$$

$$h = h_f + x h_{fg} \quad \text{wet steam with dryness fraction (x)@P}$$

$$h = h_f + h_{fg} + C_p [T_{sup} - T_s] \quad \text{superheated steam @P \& } T_{sup}$$

If h_{f1} is the specific enthalpy of water at a given feed temperature,

Then the heat gained by steam from the boiler per unit time is :

$$Q = m_s (h - h_{f1})$$

Then , the equivalent evaporation (m_e) is

$$m_e = \frac{m_s (h - h_{f1})}{h_{fg}} = \frac{m_s (h - h_{f1})}{2257}$$

Factor of evaporation Fe

- Factor of evaporation is defined as :
- “the ratio of heat received by 1kg of water under working conditions to that received by 1kg of water evaporated from and at 100 °C

$$F_e = \frac{(h - h_{f_1})}{2257}$$

Boiler efficiency

- Boiler efficiency is *“the ratio of heat actually utilized in generation of steam to the heat supplied by the fuel in the same period”*

$$\eta_b = \frac{m_a (h - h_{f1})}{C}$$

m_a – mass of water actually evaporated into steam per
kg of fuel at the working pressure

C - fuel heating value kJ/kg

Factors effecting boiler efficiency

1. Fixed Factors. These are :

(i) *Boiler design.* It includes the arrangement and effectiveness of the heating surfaces, the shape and volume of the furnace, the arrangement of flues, the arrangement of steam and water circulation.

(ii) *Heat recovery equipment.* It includes the economiser, superheater, air preheater and feed water heater.

(iii) *Built in losses.* It includes the heat transfer properties of the settings and construction materials, flue gas and ash heat losses.

(iv) Rated rate of firing, the furnace volume and heating surface.

(v) Properties and characteristics of fuel burnt.

2. Variable Factors. These are :

(i) Actual firing rate.

(ii) Fuel condition as it is fired.

(iii) The conditions of heat absorbing surfaces.

(iv) Excess air fluctuations.

(v) Incomplete combustion and combustibles in the refuse.

(vi) Change in draught from the rated, due to atmospheric conditions.

(vii) Humidity and temperature of the combustion air.

Heat losses in boiler plant

1. Heat lost to flue gases. The flue gases contain dry products of combustion as well as the steam generated due to combustion of hydrogen in the fuel.

Heat lost through *dry flue gases*,

$$Q_g = m_g c_{pg} (T_g - T_a)$$

where, m_g = Mass of gases formed per kg of coal,

c_{pg} = Specific heat of gases,

T_g = Temperature of the gases, and

T_a = Temperature of air entering the combustion chamber of boiler.

Heat carried away **by** the steam in flue gases,

$$Q_s = m_{s_1} (h_{s_1} - h_{f_1})$$

m_{s_1} = Mass of steam formed per kg of fuel due to the combustion of H_2 in the fuel,

h_{f_1} = Enthalpy of water at boiler house temperature, and

h_{s_1} = Enthalpy of steam at the gas temperature and partial pressure of steam vapour.

2. Heat lost due to incomplete combustion. The combustion is said to be incomplete if the carbon burns to CO instead of CO₂. One kg of carbon releases 10120 kJ of heat if it burns to CO whereas it can release 33800 kJ/kg if it burns to CO₂.

$$\therefore \text{Heat loss due to incomplete combustion of 1 kg of carbon} \\ = 33800 - 10120 = 23680 \text{ kJ}$$

If CO is present in the flue gases it indicates that combustion of fuel is incomplete. If the percentages of CO and CO₂ in flue gases by volume are known, then carbon burnt to CO instead of CO₂ per kg of fuel is given by

$$m_c = \frac{CO \times C}{CO_2 + CO}$$

where CO and CO₂ are expressed as % by volume in flue gases and C as the fraction of carbon in one kg of fuel.

$$\therefore \text{Heat lost due to incomplete combustion of carbon per kg of fuel}$$

$$= \frac{CO \times C}{CO_2 + CO} \times 23680 \text{ kJ/kg of fuel.}$$

This loss (due to incomplete combustion) can be reduced by supplying excess quantity of air and giving a turbulent motion to the air before it enters the furnace in order to help the mixing process.

3. Heat lost due to unburnt fuel. If m_{f_1} is the mass of unburnt fuel per kg of fuel used and C is the calorific value of the fuel, then heat lost due to unburnt fuel,

$$Q = m_{f_1} \times C$$

4. Convection and radiation losses. As the hot surfaces of the boiler are exposed to the atmosphere, therefore heat is lost to atmosphere by convection and radiation.

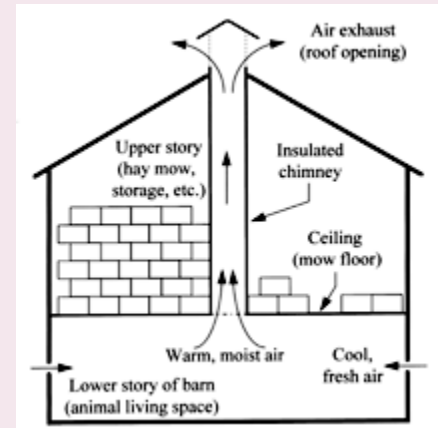
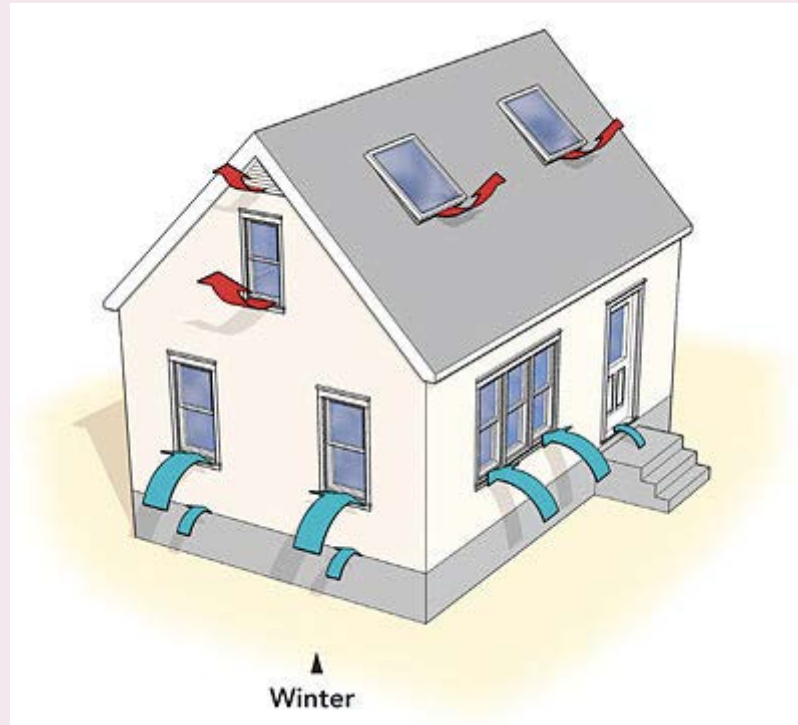
The loss of heat due to convection and radiation losses

= Heat released per kg of fuel – total of the heat losses given

Chapter Two

steam power plant

2.04 - draught



fundamentals

- **Definition**

draught is the small pressure difference which causes a flow of gas to take place.

- **Function**

in case of a boiler, draught is to :

1. **Force air to the fire.**
 2. **Carry away the gaseous products of combustion.**
- In a boiler furnace, proper combustion takes place only when sufficient quantity of air is supplied to the burning fuel.
 - **Tools**
To obtain draught as defined above and to function as stated above, the tool required is called “chimney”

Flue gas stack (chimney)

A chimney is a structure for venting hot flue gases or smoke from a boiler, stove, furnace or fireplace to the outside atmosphere.

Chimneys are typically vertical, or as near as possible to vertical, to ensure that the gases flow smoothly, drawing air into the combustion in what is known as the **stack, or chimney, effect**.

The space inside a chimney is called a flue.

Chimneys may be found in buildings, steam locomotives and ships. The term funnel is generally used for ship's chimneys and sometimes to refer to locomotive chimneys..

Chimneys are tall to increase their draw of air for combustion and to disperse pollutants in the flue gases over a greater area so as to reduce the pollutant concentrations in compliance with regulatory or other limits.

A flue gas stack is a type of chimney, a vertical pipe, channel or similar structure through which combustion product gases called flue gases are exhausted to the outside air. Flue gases are produced when coal, oil, natural gas, wood or any other fuel is combusted in an industrial furnace, a power plant's steam-generating boiler, or other large combustion device.

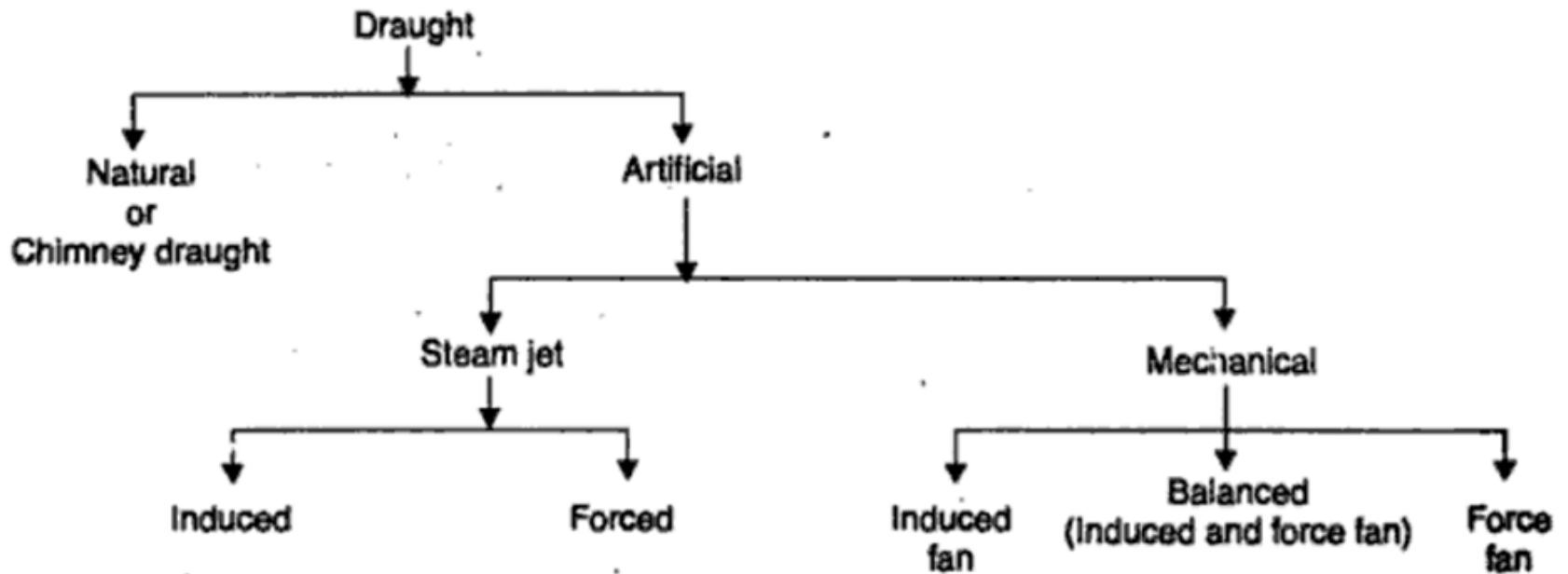
Flue gas is usually composed of carbon dioxide (CO_2) and water vapor as well as nitrogen and excess oxygen remaining from the intake combustion air. It also contains a small percentage of pollutants such as particulate matter, carbon monoxide, nitrogen oxides and sulfur oxides. The flue gas stacks are often quite tall, up to 400 meters (1300 feet) or more, so as to disperse the exhaust pollutants over a greater area and thereby reduce the concentration of the pollutants to the levels required by governmental environmental policy and environmental regulation.

When the flue gases are exhausted from stoves, ovens, fireplaces, or other small sources within residential abodes, restaurants, hotels, or other public buildings and small commercial enterprises, their flue gas stacks are referred to as chimneys.

An important note must be taken, that :

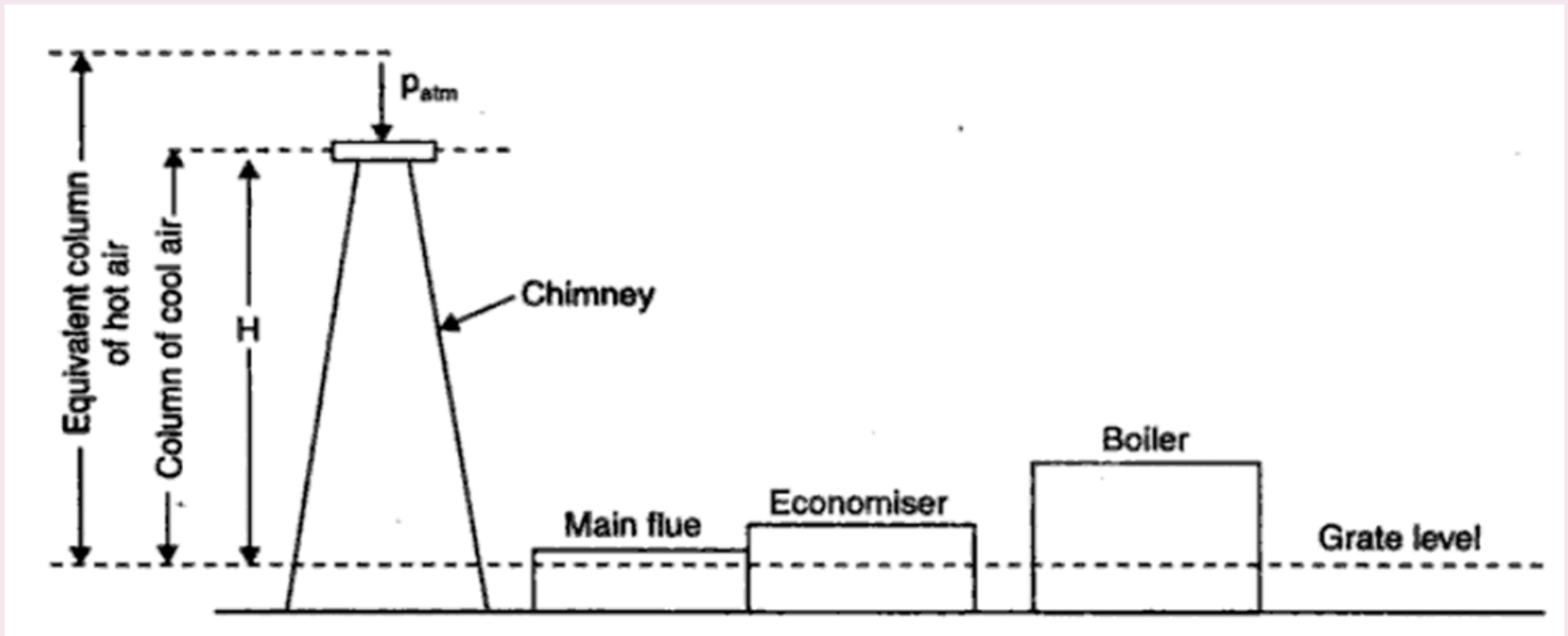
- draught is the process of induction as well as exhausting gases
- chimney is the tool through which and by which a draught is created.

Draught classification



I – natural draught

Natural draught is obtained by the use of chimney, and the draught thus Produced is due to the density difference between the column of hot gas inside the Chimney and the cold air outside.



The above figure shows a diagrammatic arrangement of a chimney of height 'H' above the grate

- Grate

It is a platform in the combustion chamber, upon which the solid fuel (wood or coal) is burnt. It generally consists of cast iron bars which are space apart so that air (required for combustion) can pass through them. The surface area of the grate, over which the fire takes place, is called grate surface.

Static draught

We have

$$p_1 = p_a + \rho_g \cdot gH$$

,

p_1 = Pressure at the grate level (Chimney side),

p_a = Atmospheric pressure at chimney top,

$\rho_g \cdot gH$ = Pressure due to the column of hot gas of height H metres, and

ρ_g = Average mass density of hot gas.

Similarly,

$$p_2 = p_a + \rho_a \cdot gH$$

p_2 = Pressure acting on the grate on the *open side*,

$\rho_a \cdot gH$ = Pressure exerted **by** the column of cold air outside the chimney of height H metres, and

ρ_a = Mass density of air outside the chimney.

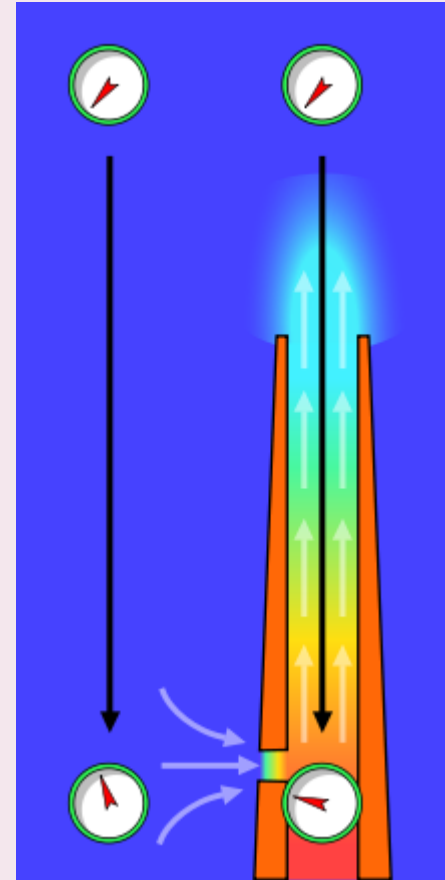
$\therefore$ Net pressure difference causing the flow through the combustion chamber,

$$\Delta p = p_2 - p_1 = (\rho_a - \rho_g) gH$$

the difference of pressure causing the flow of gases is known as "static draught"

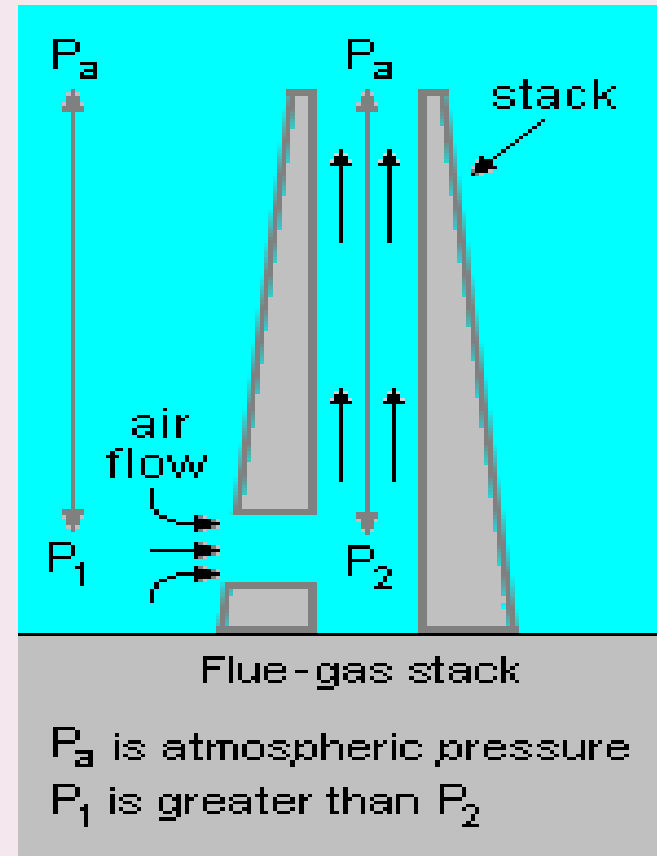
Chimney effect

- The stack effect in chimneys:
- the gauges represent absolute air pressure
- the airflow is indicated with light grey arrows.
- *The gauge dials move clockwise with increasing pressure.*



or stack effect

- **Stack effect** is the movement of air into and out of buildings, chimneys, flue gas stacks, or other containers, and is driven by a specific force.
- Such force occurs due to a difference in indoor-to-outdoor air density resulting from temperature and moisture differences.
- The result is either a positive or negative *force*.
- The greater the thermal difference and the height of the structure, the greater the force, and thus the stack effect.
- The stack effect is also referred to as the "chimney effect", and it helps drive natural ventilation and infiltration.



chimney effect calculation

The combustion flue gases inside the flue gas stacks are much hotter than the ambient outside air and therefore less dense than the ambient air. That causes the bottom of the vertical column of hot flue gas to have a lower pressure than the pressure at the bottom of a corresponding column of outside air. That higher pressure outside the chimney is the driving force that moves the required combustion air into the combustion zone and also moves the flue gas up and out of the chimney. That movement or flow of combustion air and flue gas is called "natural draft (or draught)", "natural ventilation", "chimney effect", or "stack effect". The taller the stack, the more draft (or draught) is created.

The equation below provides an approximation of the pressure difference, ΔP , (between the bottom and the top of the flue gas stack) that is created by the draft:

$$\Delta P = C . a . h . \left(\frac{1}{T_o} - \frac{1}{T_i} \right)$$

Where:

ΔP = available pressure difference, in (*Pa*)

C = 0.0342

a = atmospheric pressure, in *Pa*

h = height of the flue gas stack, in *m*

T_o = absolute outside air temperature, in (degree *K*)

T_i = absolute average temperature of the flue gas inside the stack, in *K*

Chimney Height

- Assuming that under same (T&P) conditions :
volume of combustion products = volume of air supplied
- And let :

m_a = Mass of air supplied per kg of fuel,
 $m_a + 1$ = Mass of chimney gases,
 T_a = Absolute temperature of atmosphere, and
 T_g = Average absolute temperature of chimney gases.

Also,
$$\frac{\text{Mass of hot gases}}{\text{Mass of air}} = \frac{m_a + 1}{m_a},$$

temperature and pressure being same.

Now,
$$\rho_a = \frac{p}{RT_a} = \frac{1.01325 \times 10^5}{287} \cdot \frac{1}{T_a} = 353 \cdot \frac{1}{T_a}$$

And also

$$\begin{aligned}\rho_g &= \frac{p}{RT_g} \cdot \left(\frac{m_a + 1}{m_a} \right) \\ &= \frac{1.033 \times 10^5}{287} \cdot \frac{1}{T_g} \cdot \left(\frac{m_a + 1}{m_a} \right) \\ &= 353 \cdot \frac{1}{T_g} \cdot \left(\frac{m_a + 1}{m_a} \right)\end{aligned}$$

Sub values of (ρ_a & ρ_g) in above static draught eq. $\Delta p = p_2 - p_1 = (\rho_a - \rho_g) gH$

$$\Delta p = 353 gH \left[\frac{1}{T_g} - \frac{1}{T_g} \cdot \left(\frac{m_a + 1}{m_a} \right) \right] \text{ (N/m}^2\text{)}$$

Assuming draught pressure (ΔP) is equivalent to (H_1)m height of burnt gases.

$$\Delta p = \rho_g \cdot gH_1 = 353 \left(\frac{m_a + 1}{m_a} \right) \cdot \frac{1}{T_g} g H_1$$

Equating the two expressions for (ΔP)

$$\begin{aligned} 353 \left(\frac{m_a + 1}{m_a} \right) \frac{1}{T_a} g H_1 &= 353 g H \left[\frac{1}{T_a} - \frac{1}{T_g} \left(\frac{m_a + 1}{m_a} \right) \right] \\ \frac{353}{T_a} \left(\frac{m_a + 1}{m_a} \right) g H_1 &= \frac{353}{T_g} g H - \frac{353}{T_g} g H \left(\frac{m_a + 1}{m_a} \right) \\ \frac{353}{T_a} \left(\frac{m_a + 1}{m_a} \right) g H_1 &= \frac{353}{T_g} \left(\frac{m_a + 1}{m_a} \right) g H \left[\left(\frac{m_a}{m_a + 1} \right) \frac{T_g}{T_a} - 1 \right] \\ \therefore H_1 &= H \left[\left(\frac{m_a}{m_a + 1} \right) \frac{T_g}{T_a} - 1 \right] \end{aligned}$$

Let (h_w) be the height of water column in (mm) shown by U-tube manometer
Which will produce (ΔP)

$$\begin{aligned} h_w &= 353 H \left[\frac{1}{T_a} - \frac{1}{T_g} \left(\frac{m_a + 1}{m_a} \right) \right] \\ (1 \text{ mm of water} &= 9.81 \text{ Pa}) \end{aligned}$$

Chimney diameter

- Assuming no losses, the velocity of the gases passing through the chimney is expressed as:
- $C = \sqrt{2gH_1}$
- If there is losses, then the pressure loss in the chimney is equivalent to a hot gas column of (h^-), then
- $C = \sqrt{2g(H_1 - h^-)}$
 $= 4.43 \sqrt{(H_1 - h^-)}$
 $= 4.43 \sqrt{(1 - h^- / H_1)} [\sqrt{H_1}]$
 $= K [\sqrt{H_1}]$
- Where
- $K = 0.825$ for brick chimney
 $= 1.1$ for steel chimney

The mass of the gases flowing through any cross section is given by:

$$\dot{m}_g = \rho_g \cdot A \cdot C \quad \text{kg/s}$$

and since

$$A = \pi/4 \ D^2$$

Then chimney diameter can be evaluated in terms of other variables, where (C) and (ρ_g) evaluation as derived above. The final form of chimney diameter evaluation can be presented as

$$D = 1.128 \sqrt{\frac{\dot{m}_g}{\rho_g \cdot C}}$$

where, $\dot{m}_g$ = Mass of gases flowing through any cross-section of the chimney,

ρ_g = Density of gases, and

C = Velocity of gases passing through the chimney.

The flue gas flow rate induced by the draft

As a "first guess" approximation, the following equation can be used to estimate the flue gas flow rate induced by the draft of a flue gas stack. The equation assumes that the molar mass of the flue gas and the outside air are equal and that the frictional resistance and heat losses are negligible :

$$Q = C . A . \sqrt{2 g h \left(\frac{[T_i - T_o]}{T_i} \right)}$$

where:

Q = flue gas flow rate, m³/s

A = cross-sectional area of chimney, m² (assuming it has a constant cross-section)

C = discharge coefficient (usually taken to be from 0.65 to 0.70)

g = gravitational acceleration at sea level, 9.807 m/s²

h = height of chimney, m

T_i = absolute average temperature of the flue gas in the stack, K

T_o = absolute outside air temperature, K

Max draught

- The chimney draught is most effective when the max weight of hot gases is discharged in a given time.
- This will occur when :

$$T_g = f(T_a)$$

The gas velocity when the losses to be negligible is

$$C = \sqrt{2gH_1}, \text{ where } h' = 0$$

and since

$$H_1 = H \left[\left(\frac{m_a}{m_a + 1} \right) \frac{T_g}{T_a} - 1 \right]$$

Sub (H_1) in velocity equation

$$C = \sqrt{2gH \left[\left(\frac{m_a}{m_a + 1} \right) \frac{T_g}{T_a} - 1 \right]}$$

The density of the hot gases

$$\rho_g = \frac{p}{RT_g}$$

The mass of the gas discharged per second

$$m_g = A \times C \cdot \rho_g$$

Inserting values of C & gas density to get

$$m_g = A \sqrt{2gH \left[\left(\frac{m_a}{m_a + 1} \right) \frac{T_g}{T_a} - 1 \right]} \frac{p}{RT_g}$$

$$m_g = \frac{K}{T_g} \sqrt{\left(\frac{m_a}{m_a + 1} \right) \frac{T_g}{T_a} - 1}$$

constant $K = \frac{A \times p \times \sqrt{2gH}}{R}$

Condition for maximum discharge through a chimney is : $\frac{T_g}{T_a} = 2 \left(\frac{m_a + 1}{m_a} \right)$.

II - Artificial draught

In the boiler installations of today the total static draught required may vary from 30 to 350 mm of water column.

It may not be possible to build a chimney high enough to produce draught of such a large magnitude. To meet this requirement artificial draught system should be used. It may be a *mechanical draught* or a *steam jet draught*. The former is used for central power stations and many other boiler installations while the latter is employed for small installations and in locomotives.

II.A – Mechanical draught

- The common methods applied for mechanical draught in steam power plants are :
 1. Forced draught
 2. Induced draught
 3. Balanced draught

1 - Forced draught

In a mechanical draught system, the draught is produced **by** a fan. In a forced draught system, a blower or a fan is installed *near or at the base of the boiler* to force the air through the cool bed and other passages through the furnace, flues, air preheater, economiser etc. It is a *positive pressure draught*. *The enclosure for the furnace etc. has to be very highly sealed so that gases from the furnace do not leak out in the boiler house.*

2 – induced draught

In this system a fan or blower is located *at or near the base of the chimney*. The pressure over the fuel bed is reduced below that of the atmosphere. **By** creating a partial vacuum in the furnace and flues, the products of combustion are drawn from the main flue and they pass up the chimney. *This draught is used usually when economisers and air preheaters are incorporated in the system.* The draught is similar in action to the natural draught.

3 – balance draught

It is a combination of the forced and induced draught systems. In this system the forced draught fan overcomes the resistance in the air preheater and chain grate stoker while the induced draught fan overcomes draught losses through boiler, economiser, air preheater and connecting flues.

The forced draught entails following advantages over induced draught :

- 1. Forced draught fan does not require water cooled bearings.*
- 2. Tendency to air leak into the boiler furnace is reduced.*
- 3. No loss due to in rush of cold air through the furnace doors when they are opened for fire and cleaning fires.*
- 4. Fan size and power required for the same draught are 1/5 to 1/2 of that required from an induced draught fan installation because forced draught fan handles cold air.*

II.B - Steam jet draught

Steam jet draught is a simple and easy method of producing artificial draught. It may be forced or induced type depending upon where the steam jet to produce draught is located. If the steam jet is *directed into the smoke box* near the stack, the air is *induced* through the flues, the grate and ash pit to the smoke box. If the jet is *located before the grate*, air is *forced* through the fuel bed, furnace and flues to the chimney.

The steam jet draught entails the following *advantages* :

- (i) Very simple and economical.
- (ii) Occupies minimum space.
- (iii) Requires very little attention.
- (iv) In forced type steam jet draught, the steam keeps the fire bars cool and prevents the adhering of clinker to the fire bars.
- (v) Several classes of low grade fuels can be used with this system.

Designing chimneys and stacks to provide the correct amount of natural draft involves a great many factors such as :

- 1. The height and diameter of the stack .*
- 2. The desired amount of excess combustion air needed to assure complete combustion .*
- 3. The temperature of the flue gases leaving the combustion zone .*
- 4. The composition of the combustion flue gas, which determines the flue gas density.*
- 5. The frictional resistance to the flow of the flue gases through the chimney or stack, which will vary with the materials used to construct the chimney or stack .*
- 6. The heat loss from the flue gases as they flow through the chimney or stack .*
- 7. The local atmospheric pressure of the ambient air, which is determined by the local elevation above sea level .*

The calculation of many of the above design factors requires trial-and-error iterative methods.

tutorial

- All chimneys produce a suction at their base due to the difference in density of the hot flue gases rising in the chimney.

Suction Effect = Weight of air column at T_{amb} - weight of column of hot flue gases.

- Or;
- $\Delta p = H \times g (\rho_{air} - \rho_{flue\ gas})$
- where;
- Δp = suction pressure or draught (N/m^2) obtained from boiler catalogue.
- H = height of column (m) or chimney height
- g = acceleration due to gravity ($9.81\ m/s^2$)
- ρ = density (kg/m^3)
- Chimney or Flue height can be determined from the following;
- $H = \Delta p / [g (\rho_{air} - \rho_{flue\ gas})]$

Example 1

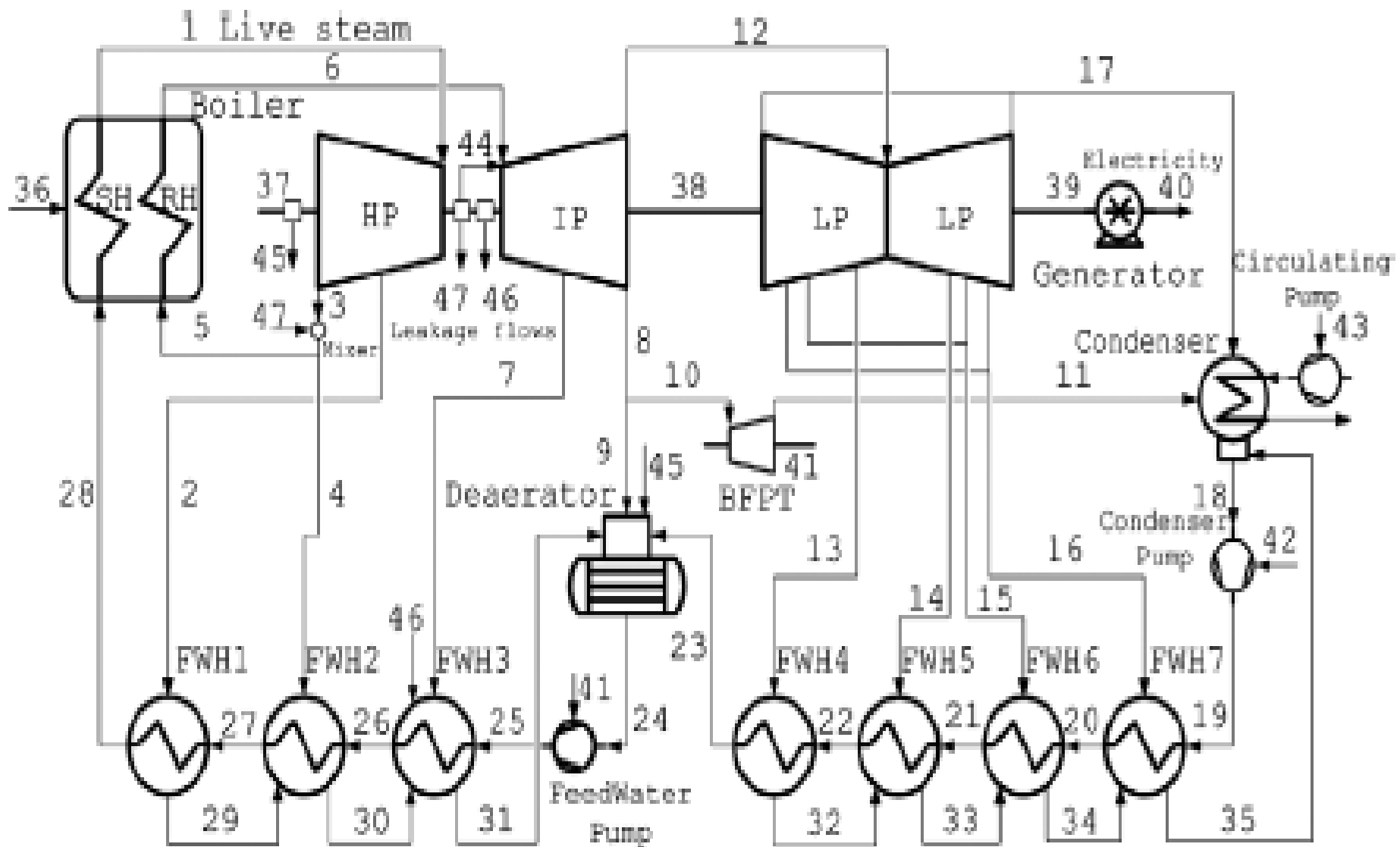
- Calculation the minimum flue height for an oil fired boiler and determine a suitable termination height for the flue given the following information;
- DATA
- Building height at eaves level = 6 metres.
- Height of roof ridge = 8 metres.
- Height of highest openable window = 3.2 metres.
- Outside air density = 1.2 kg/m^3 .
- Flue gas density = 1.0 kg/m^3 .
- Minimum flue gas suction pressure at boiler = $6 \text{ Pa (N/m}^2\text{)}$.
- Pressure loss in straight flue and flue fittings = 4 Pa .
- Answer
-
- Flue Gas Suction Pressure required = minimum boiler suction pressure + Flue pressure losses.
- Flue gas Pressure required at boiler = $6 + 4 = 10 \text{ Pa}$
-
- Minimum flue height:
-
- $$H = \Delta p / [g (\rho_{\text{air}} - \rho_{\text{flue gas}})]$$
-
- $$H = 10 / [9.81 (1.2 - 1.0)]$$
-
- $$H = 10 / 1.962 = 5.097 \text{ metres.}$$
-
- A suitable termination height would be 6 metres since this is; more than the calculated minimum height, above openable windows, lower than the ridge height and at eaves level.

Chapter two

steam power plant

2.05.1 – Condenser

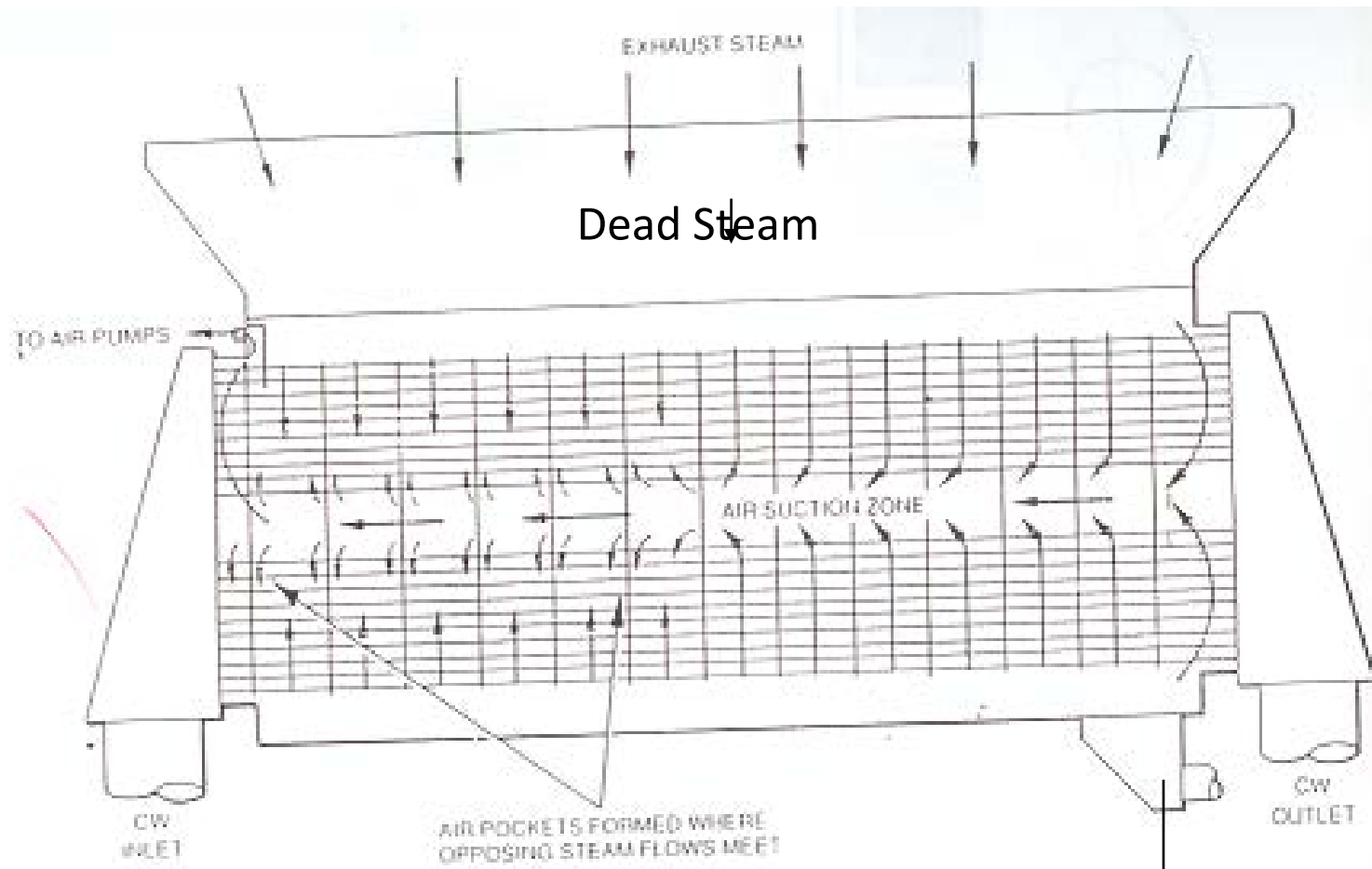
Flow Cycling : A Holistic Process in for A Power Plant



Steam Condenser

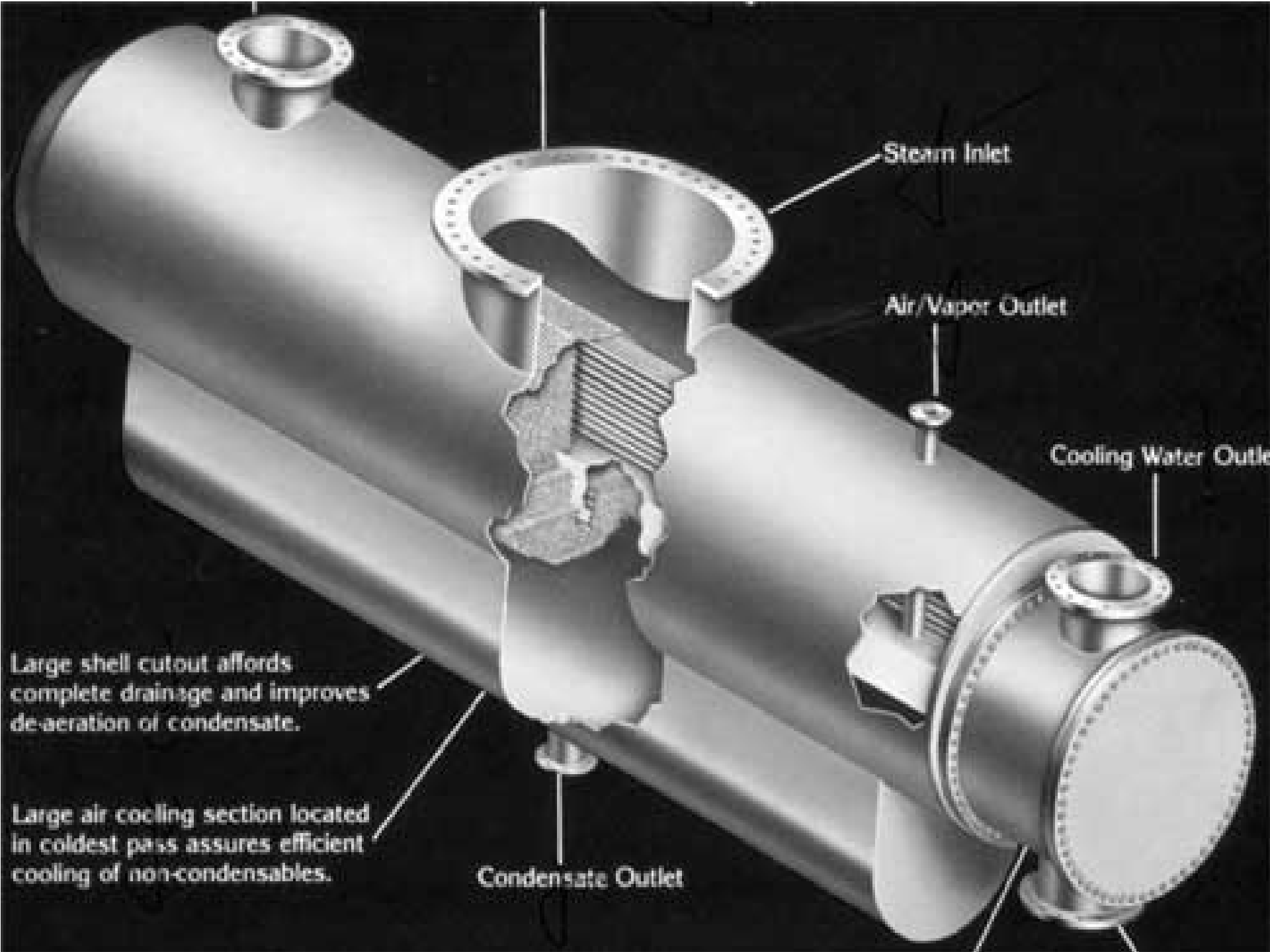
- Steam condenser is a closed space into which steam exits the turbine and is forced to give up its latent heat of vaporization. It is therefore :
- A device which makes power plant a true cycle..
- A device solely responsible for recycling of working fluid
- It is a necessary component of a steam power plant because of two reasons:
 1. It converts dead steam into live feed water.
 2. It lowers the cost of supply of cleaning and treating of working fluid.
- It is far easier to pump a liquid than a steam.
- It increases the efficiency of the cycle by allowing the plant to operate on largest possible temperature difference between source and sink.
- The steam's latent heat of condensation is passed to the water flowing through the tubes of condenser.
- After steam condenses, the saturated water continues to transfer heat to cooling water as it falls to the bottom of the condenser called, hot-well.
- This is called sub-cooling and certain amount is desirable.
- The difference between saturation temperature corresponding to condenser vacuum and temperature of condensate in *hot-well* is called "condensate depression".

A Device to Convert Dead Steam into Live Water



Water ready to take
Rebirth





Steam Inlet

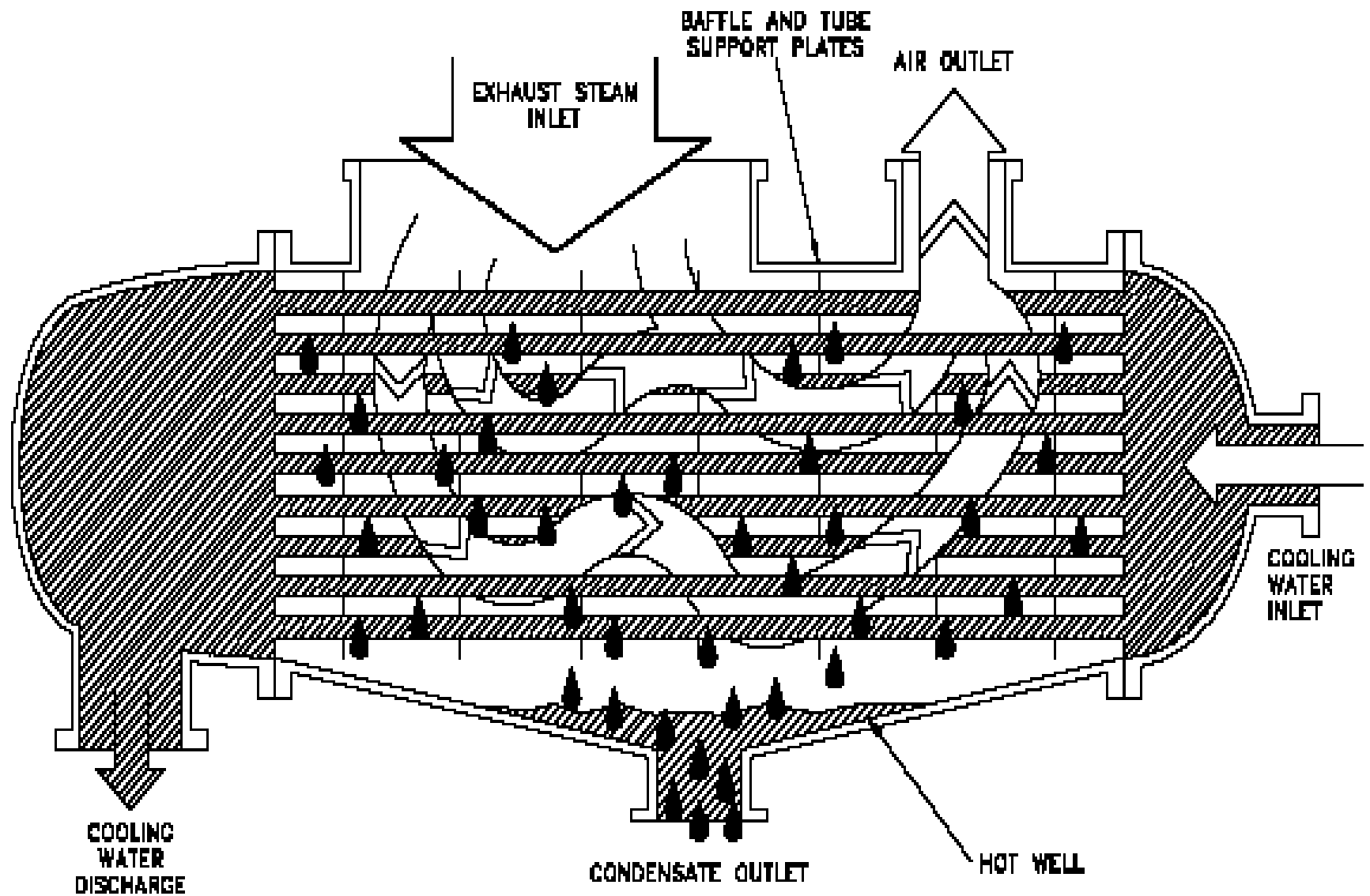
Air/Vapor Outlet

Cooling Water Outlet

Condensate Outlet

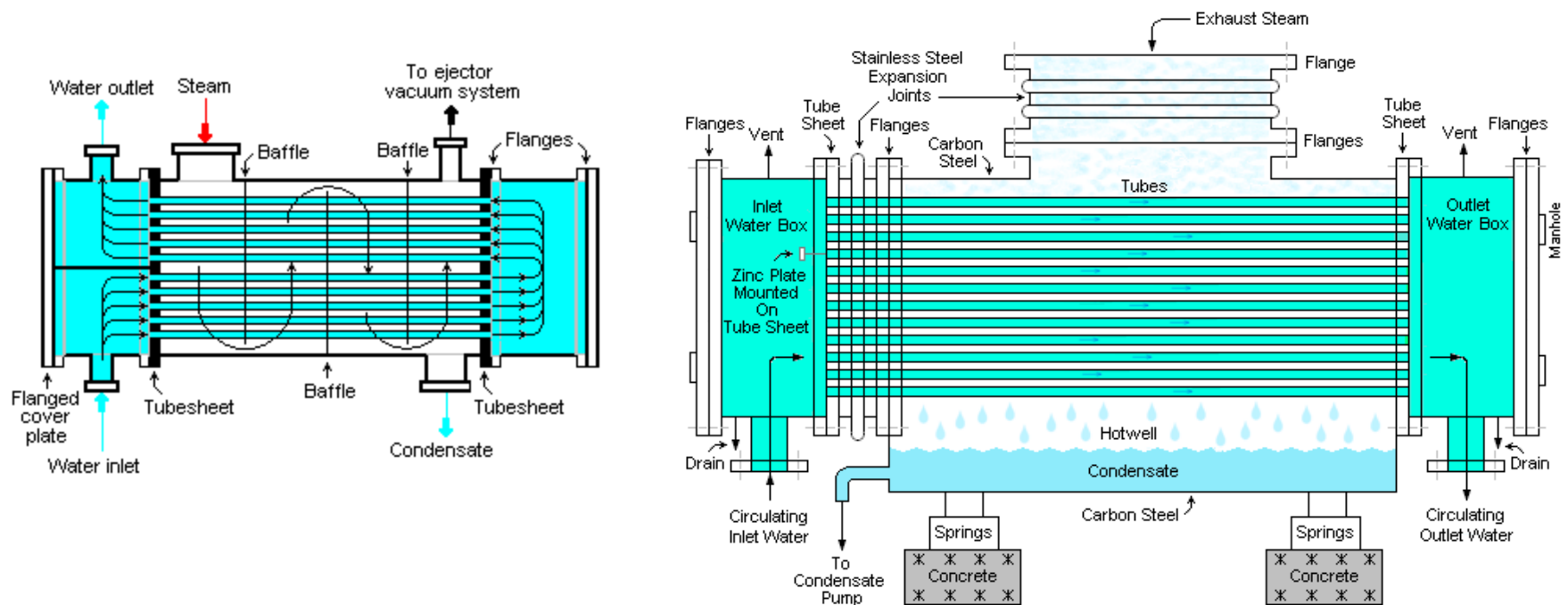
Large shell cutout affords complete drainage and improves de-aeration of condensate.

Large air cooling section located in coldest pass assures efficient cooling of non-condensables.



Single-Pass Condenser

Cross-sectional schematic diagram of a [power plant condenser](#) for condensing exhaust steam from a [steam turbine](#). This condenser is single-pass on both the tube and shell sides with a large opening at the top for the exhaust steam to enter and a **hotwell** at the bottom where [condensate](#) water drips down to and collects. Circulating water for cooling is shown in light greenish color and condensate is light blue. Note also that the springs at the condenser support pads or the expansion joint at the turbine exhaust are designed in for thermal expansion and a normal installation includes either one or the other, not both like in this diagram.



Note: Tubes are brass, cupro nickel, titanium or stainless steel. The tubes are expanded or rolled and bell mouthed at the ends in the tubesheets.

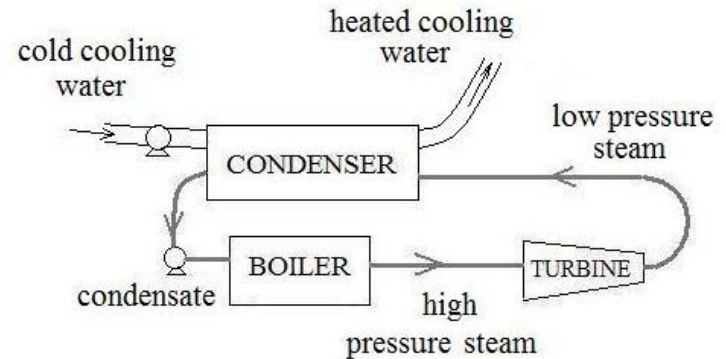
Typical Power Plant Condenser

Types

- The condensing unit is a crucial part of a steam power plant water circulation system, whereby water going through the condensing unit must be cooled down in order to convert low pressure steam leaving the turbine to liquid condensate that can be pumped back into the boiler.
- Cooling for the condenser may be supplied by:
 1. once through cooling, water is discharged back to the source body of water at an elevated temperature.
 2. a wet cooling tower, that provides evaporative cooling
 3. dry (air) cooling, an air cooled condenser.
 4. a hybrid (wet/dry) system, wet/dry cooling system (primarily air cooled with evaporative cooling use as needed),
 5. a cooling pond.

1 – Once through cooling

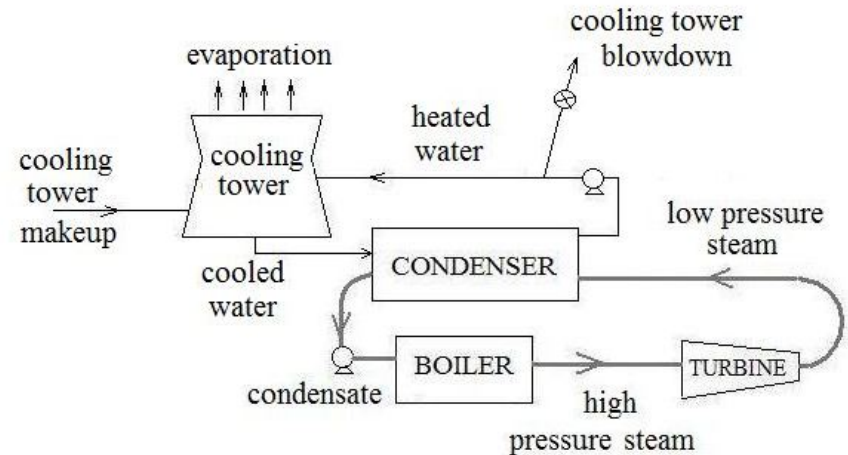
cooling water is withdrawn, typically from a surface water body, with heated water from the condenser discharged back to the surface water body. This type of condenser cooling withdraws water from the source water body at a very great rate. It returns almost all of that water to the source water body, but at an elevated temperature. This is also known as 'open type cooling system.



Steam Power Plant Rankine Cycle
with Once Through Cooling

2 – wet cooling system

An alternative cooling method that requires much less cooling water withdrawal from the source water body is the wet cooling tower. The diagram below shows the general flow patterns. The heated water leaving the condenser passes through a cooling tower and is cooled by evaporative cooling. This type of cooling system withdraws much less water from the source water body, but it consumes much more water than the once through system, due to evaporation into the atmosphere.



Steam Power Plant Rankine Cycle
with Wet Cooling Tower

3 – dry cooling system

- An air cooled condenser provides a means of condensing steam without using cooling water, when a lack of water prevents use of a traditional water cooled condenser in a steam power plant.
- There is increasing interest in use of the air cooled condenser, also called a dry cooling tower, for steam power plant water condensing due to competition from other sectors for use of scarce water resources
- Dry cooling, utilizing an air cooled condenser, is illustrated in the diagram below. The air cooled condenser, often referred to as 'dry cooling,' eliminates the need for steam power plant water use for cooling.
- There has been increasing interest in dry cooling/air cooled condenser use, because of increased concern about and regulation of water use for [electric power](#) production. The dry cooling option, however, comes at an increased initial cost, increased operating cost and increased heat rate (decreased efficiency), leading to increased cost for production of electricity.
- Recently hybrid wet/dry systems are being developed and put into use, with less cost and less efficiency penalty than strictly dry cooling

An air cooled condenser used in a steam power plant has two options for air movement:

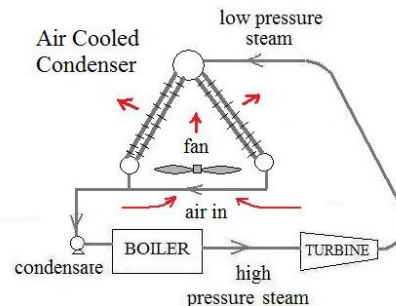
- i - natural draft
- ii - mechanical draft.

The most common type of air cooled condenser is the mechanical draft

The typical flow pattern of steam, air and condensate is shown in the schematic diagram below. The low pressure steam exhausted from the turbine goes into the air cooled condenser in the large tube shown at the top of the A-frame in the picture. The steam flows down through finned tubes that make up the A-frame and is cooled and condensed by air being blown past the finned tubes by a fan or fans at the bottom



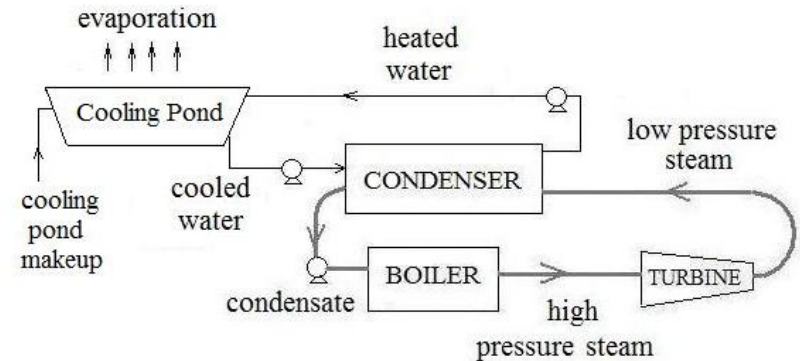
Air Cooled Condenser



Steam Power Plant Rankine Cycle
with Air Cooled Condenser

4 – cooling pond

- A final option is use of a cooling pond as shown in the diagram below.
- The water consumption is about the same as for a wet cooling tower, because the cooling in the pond is primarily due to evaporation



Steam Power Plant Rankine Cycle
with Cooling Pond

Comparison of Alternatives

- Steam power plant cooling water is used primarily for the condensing unit. The cooling alternatives, once through cooling, wet cooling tower, air cooled condenser, hybrid wet/dry cooling, and cooling ponds each have advantages and disadvantages.
- Steam power plant cooling water use has been coming under increasing scrutiny because of the large quantities of water involved and the many competing uses for water.
- Here the condenser/cooling options will be compared in terms of :
 - i - water withdrawal,
 - ii - water consumption,
 - iii - economics
 - iv - percentage of generating capacity using each option.

i & ii – water withdrawal & consumption

A comparison of typical water withdrawal rates and water consumption rates is given in the table below, for once-through cooling, cooling tower, and cooling pond systems, with fossil fueled and nuclear fueled steam power plants.

The water withdrawal rate for once through cooling is two orders of magnitude larger than that for pond or cooling tower systems.

The withdrawal rate for pond and cooling tower systems is simply replacement for the water evaporation into the atmosphere.

There are only small differences in the rate of water consumption for the three systems.

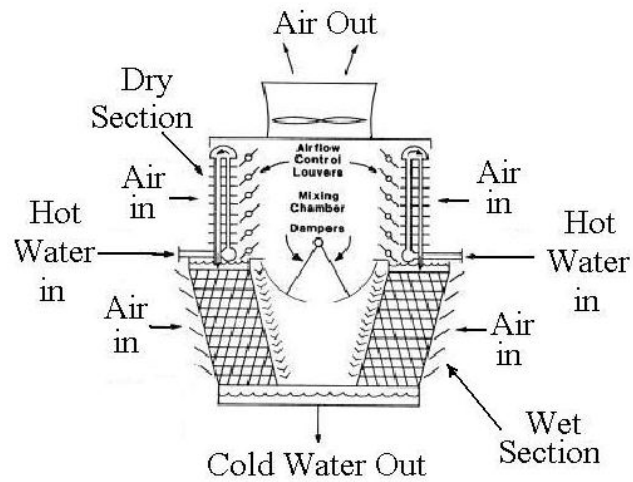
Steam Power Plant & Cooling System Type	Water Withdrawal (gal/MWh)	Typical Water Consumption (gal/MWh)
Fossil/biomass/waste fueled once-through cooling	20,000 to 50,000	~300
Fossil/biomass/waste fueled pond cooling	300 to 600	300-480
Fossil/biomass/waste fueled cooling tower	500 to 600	~480
Nuclear fueled once-through cooling	25,000 to 60,000	~400
Nuclear fueled pond cooling	500 to 1100	400-720
Nuclear fueled cooling tower	800 to 1100	~720

iii - Hybrid Wet and Dry Cooling

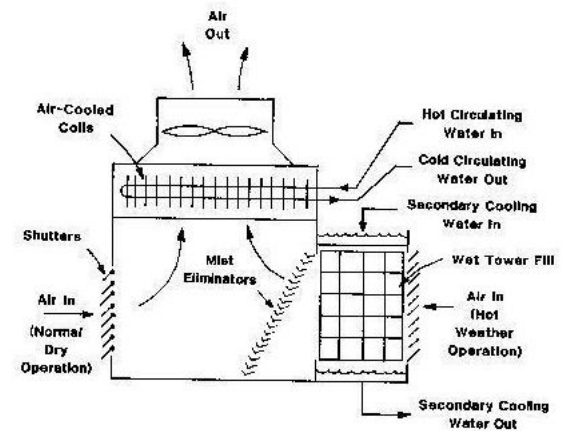
- The air cooled condenser is seeing increased use for steam power plant condenser cooling because of increasing concern about the extent of power plant water usage for condenser cooling.
- Use of an air cooled condenser drastically reduces the rate of power plant water usage, but at the expense of increased capital cost, increased operating cost and a reduction in power production efficiency, especially in hot weather.
- An air cooled condenser with an added evaporative cooling component has come to be called a hybrid wet and dry cooling system. This combination provides the possibility of eliminating most of the efficiency penalty with only a small increase in power plant water usage.
- Both wet and dry components (evaporative cooling and an air cooled condenser) are included in a hybrid wet and dry steam power plant condenser cooling system. The evaporative cooling and air cooled condenser components may be used separately or they may be combined in one unit.
- The followings are examples of such hybrid cooling :

Water Spray Enhancement for an Air Cooled Condenser

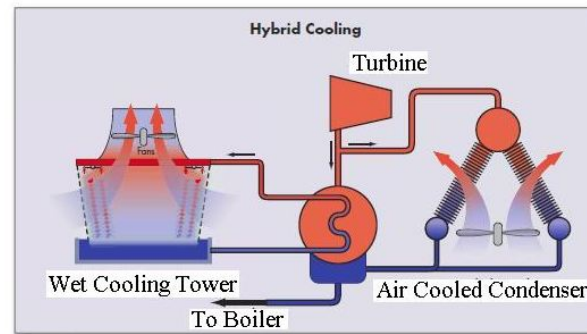
- While the air cooled condenser has a significant advantage over once through cooling or a cooling tower in terms of water requirements, a steam power plant with a dry cooling tower / air cooled condenser system will typically have **reduced plant efficiency and output in the hotter part of the year**. A technique being investigated for improving plant efficiency and output in hot weather is **inlet spray cooling**, that is, spraying water into the air entering the condenser during the hot part of the year, when reduced plant efficiency and output are of concern. This is one of the ways of combining characteristics of a wet and dry cooling tower, referred to as hybrid wet/dry cooling



Single Tower - Plume Abatement



Single Tower Hybrid Cooling



Hybrid Wet and Dry Cooling

iv - Economic Comparison

There is a reason that **once through cooling** was used in almost all steam power plants built before 1970.

as It has the following advantages :

- i - the simplest system
- ii - the least initial cost
- iii - the least operating cost.

Both the **wet cooling** tower system and the **air cooled** condenser (dry cooling) system have **higher capital cost, higher power requirement** (and thus higher operating cost), leading to approximately **1.9 %** higher cost of electricity due to use of a wet cooling tower and approximately **4.9 %** higher cost of electricity for air cooled condenser use, as shown in the table below.

Items for Comparison	Type of Cooling System		
	Once Through	Wet Tower	Dry Cooling
Capital Cost	base	base + 0.4%	base + 12.5%
Cooling System Power	base	base + 2.5 MW	base + 3.0 MW
Plant Heat Rate	base	base + 0.4%	base + 4.0%
Power Production Cost	base	base + 1.9%	base + 4.9%

v - Percentage of Use

Four types of condenser/cooling systems, is shown in the table below.

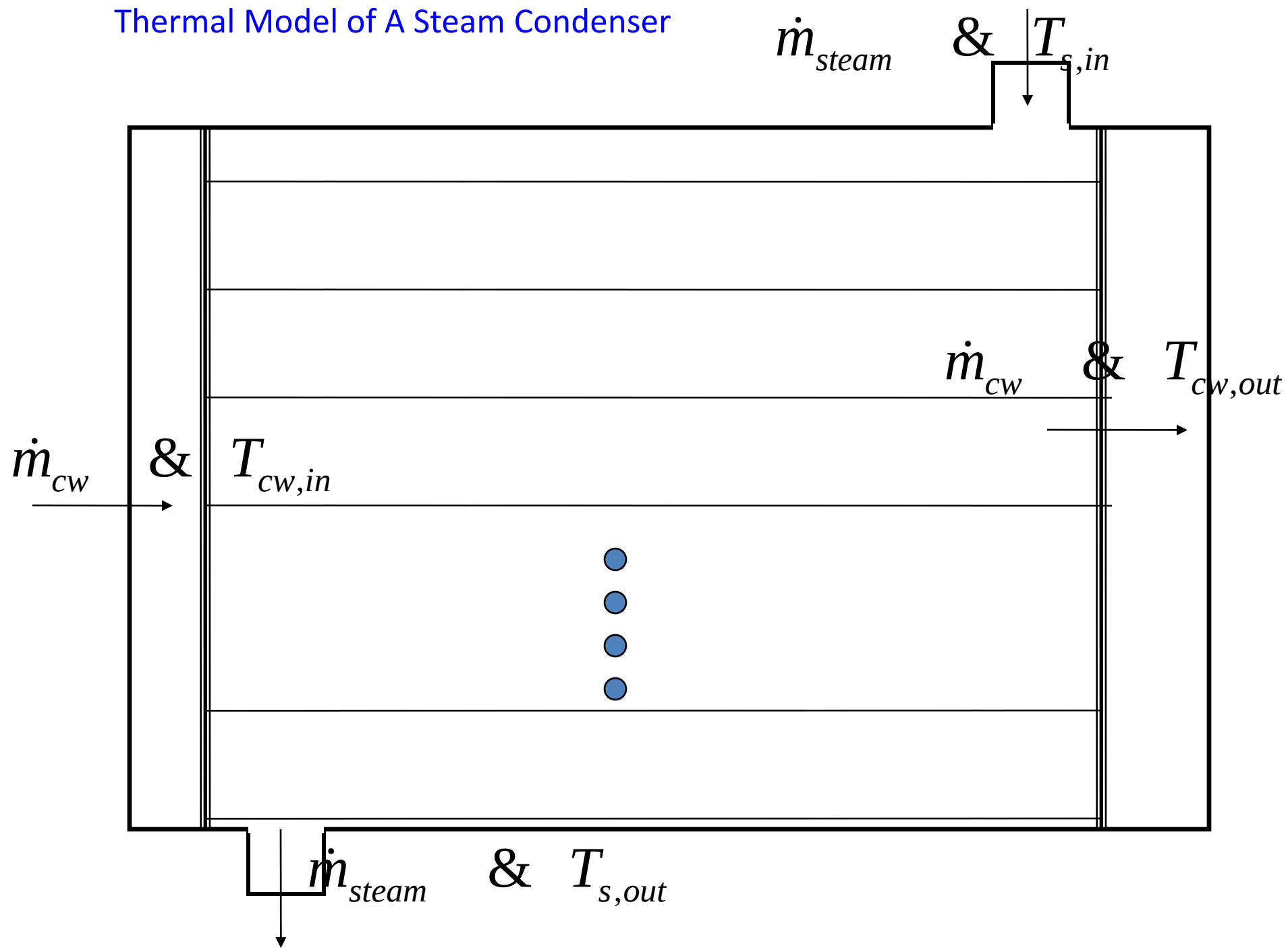
Most of the steam power plants built in the U.S. before 1970 use once through cooling. Due to increasing concern about and regulation of water use for electric power production, Most of those built after 1970 use cooling towers.

These two types of condenser cooling systems account for about 84 % of steam power plants.

Most of the rest use cooling ponds. Dry cooling has emerged as another option because of the water withdrawal and consumption rates for the other options, even with wet cooling towers. About 1 % of steam power plants use an air-cooled condenser (dry cooling system).

Generation Type	Percentage (%)			
	Cooling Tower	Once Through	Air-cooled Condenser	Cooling Pond
Coal	48.0%	39.1 %	0.2%	12.7%
Fossil Non-Coal	23.8%	59.2 %	0.0%	17.1%
Combined Cycle	30.8%	8.6%	59.0%	1.7%
Nuclear	43.6%	38.1%	0.0%	18.3%
Total	41.9%	42.7%	0.9%	14.5%

Thermal Model of A Steam Condenser



Condenser heat balance =

The heat balance of the condenser under the assumption of ideal conditions is that :

The heat gained by the cooling water is equal to heat lost from Steam .

$$\begin{aligned} Q &= \dot{m}_{cw} (T_{cw_{out}} - T_{cw_{in}}) \\ &= \dot{m}_{st} (T_{st_{in}} - T_{st_{out}}) \end{aligned}$$

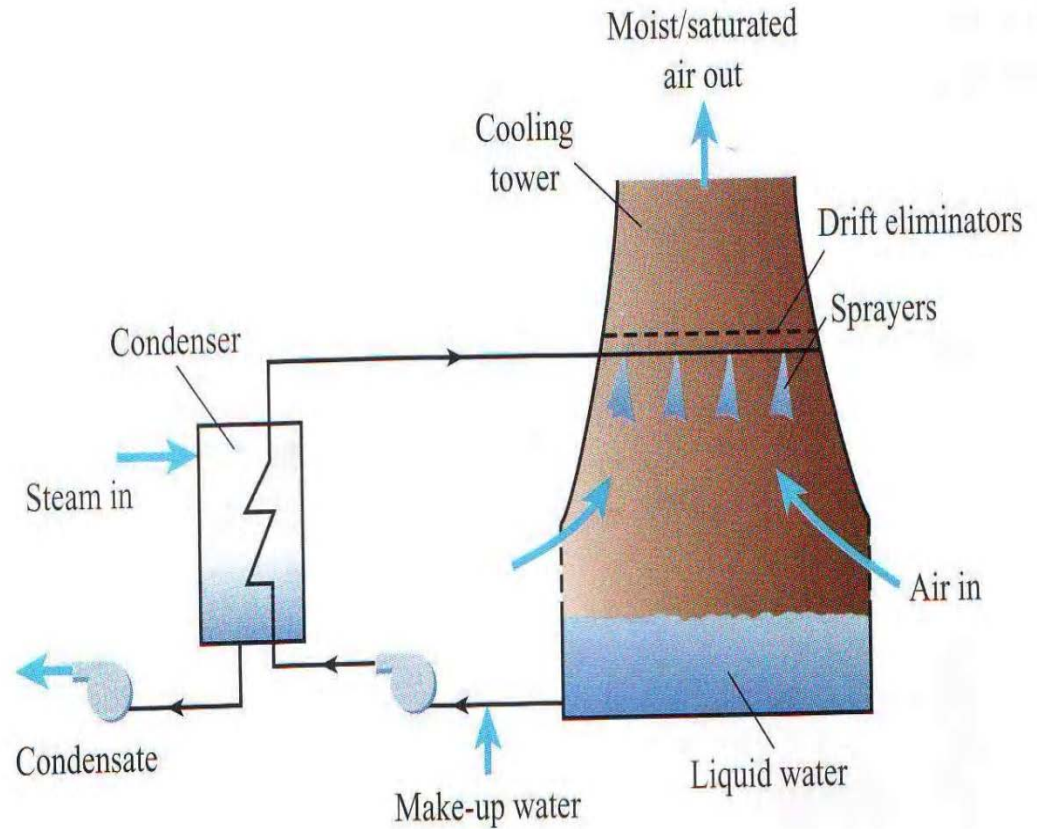
Chapter two

steam power plant

2.05.2 - COOLING TOWER

COOLING TOWER

Schematic diagram of a cooling tower used in steam power plants. Hot water is sprayed in the cooling tower and cooled by the air that enters at the base of the tower. The cold water is then pumped to the steam condenser.

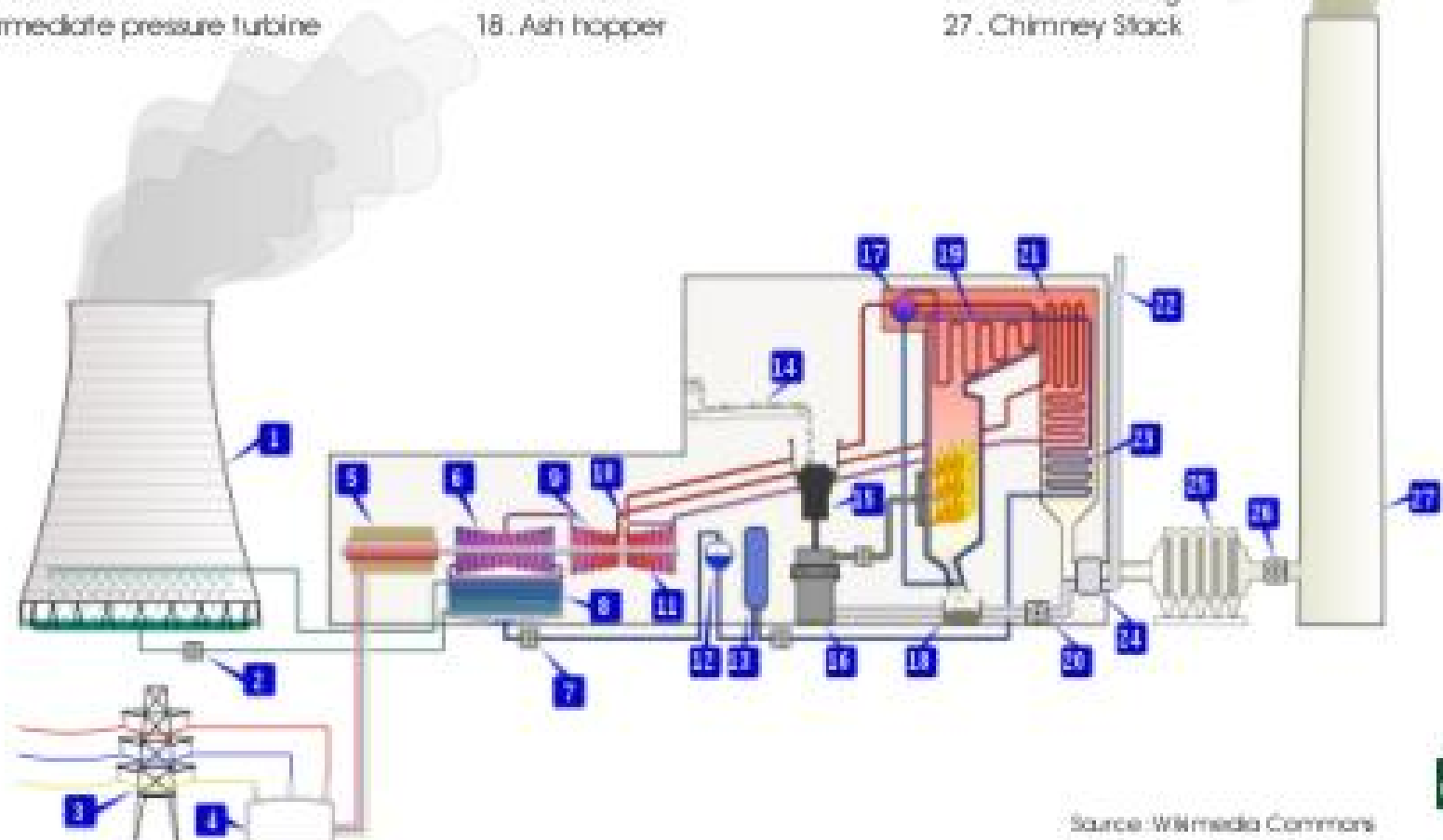




1. Cooling tower
2. Cooling water pump
3. Transmission line (3-phase)
4. Unit transformer (3-phase)
5. Electric generator (3-phase)
6. Low pressure turbine
7. Condensate extraction pump
8. Condensor
9. Intermediate pressure turbine

10. Steam governor valve
11. High pressure turbine
12. Deaerator
13. Feed heater
14. Coal conveyor
15. Coal hopper
16. Pulverised fuel mill
17. Boiler drum
18. Ash hopper

19. Superheater
20. Forced draught fan
21. Reheater
22. Air intake
23. Economiser
24. Air preheater
25. Precipitator
26. Induced draught fan
27. Chimney stack



Source: Wikimedia Commons



introduction

- **Cooling towers** are heat removal devices used to transfer process waste heat to the [atmosphere](#).
- Cooling towers may either use the [evaporation](#) of water to remove process heat and cool the working fluid to near the [wet-bulb air temperature](#) or rely solely on air to cool the working fluid to near the [dry-bulb air temperature](#) .
- Common applications include cooling the circulating water used in [oil refineries](#), [chemical plants](#), [power stations](#) and building cooling.
- The towers vary in size from small roof-top units to very large [hyperboloid structures](#) (as in above) that can be up to 200 metres tall and 100 metres in diameter, or [rectangular structures](#) that can be over 40 metres tall and 80 metres long.
- Smaller towers are normally factory-built, while larger ones are constructed on site.

Classification

- Cooling towers as defined above can be identified in various methods, and this in other words an attempt to classify such element

1 - Classification by use

- Cooling towers can generally be classified by use into either HVAC (air-conditioning) or *industrial* duty.
- **HVAC**
- An HVAC cooling tower is a subcategory rejecting heat from a chiller. Water-cooled chillers are normally more energy efficient than air-cooled chillers due to heat rejection to tower water at or near wet-bulb temperatures. Air-cooled chillers must reject heat at the dry-bulb temperature, and thus have a lower average reverse-Carnot cycle effectiveness. Large office buildings, hospitals, and schools typically use one or more cooling towers as part of their air conditioning systems. Generally, industrial cooling towers are much larger than HVAC towers

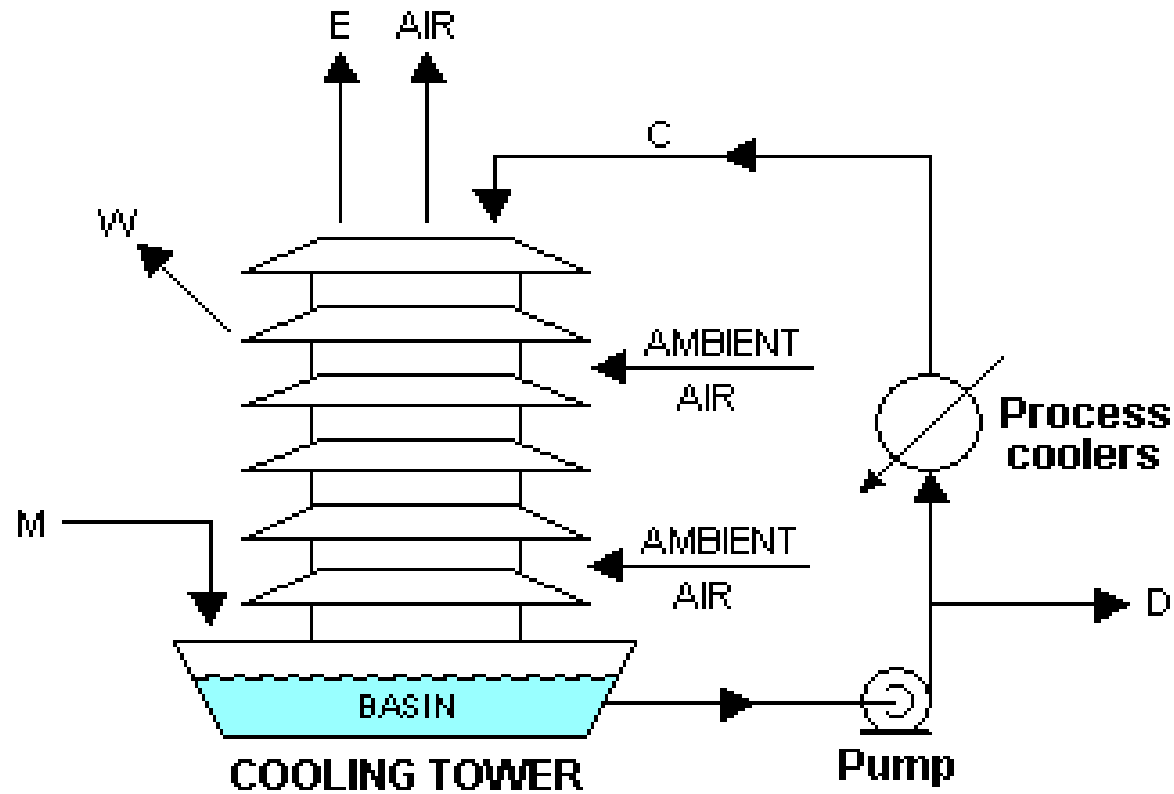
Industrial cooling towers

- Industrial cooling towers can be used to remove heat from various sources such as machinery or heated process material .
- The primary use of large, industrial cooling towers is:
 1. to remove the heat absorbed in the circulating cooling water systems used in [power plants](#), [petroleum refineries](#), [petrochemical](#) plants, [natural gas](#) processing plants, food processing plants, semi-conductor plants, and other industrial facilities.
 2. The circulation rate of cooling water in a typical 700 MW [coal-fired power plant](#) with a cooling tower amounts to about 71600 cubic metres an hour (315000) U.S. gallons per minute
 3. and the circulating water requires a supply water make-up rate of perhaps 0.5 percent i.e 0.5(3600) cubic metres an hour

2 - Heat transfer methods

- With respect to the [heat transfer](#) mechanism employed, the main types are:
 1. *Wet cooling towers* or simply *cooling towers* operate on the principle of [evaporation](#). The working fluid and the evaporated fluid (usually H₂O) are one and the same .
 2. *Dry coolers* operate by [heat transfer](#) through a surface that separates the working fluid from ambient air, such as in a [heat exchanger](#), utilizing convective heat transfer. They do not use evaporation .
 3. *Fluid coolers* are hybrids that pass the working fluid through a tube bundle, upon which clean water is sprayed and a fan-induced draft applied. The resulting heat transfer performance is much closer to that of a wet cooling tower, with the advantage provided by a dry cooler of protecting the working fluid from environmental exposure

COOLING TOWER SYSTEM



- C = CIRCULATING COOLING WATER
- E = EVAPORATED WATER
- W = WINDAGE or DRIFT LOSS
- M = MAKEUP WATER
- D = DRAW/OFF or BLOW/DOWN WATER

3 - Air flow generation methods

- With respect to drawing air through the tower, there are three types of cooling towers:
- Natural draft, which utilizes buoyancy via a tall chimney. Warm, moist air *naturally* rises due to the density differential to the dry, cooler outside air. Warm moist air is less dense than drier air at the same pressure. This moist air buoyancy produces a current of air through the tower .
- Mechanical draft, which uses power driven fan motors to force or draw air through the tower .
 - *Induced draft*: A mechanical draft tower with a fan at the discharge which pulls air through tower. The fan *induces* hot moist air out the discharge. This produces low entering and high exiting air velocities, reducing the possibility of *recirculation* in which discharged air flows back into the air intake. This fan/fill arrangement is also known as *draw-through*. (see Image ٢, (٢
- Forced draft: A mechanical draft tower with a blower type fan at the intake. The fan *forces* air into the tower, creating high entering and low exiting air velocities
- Fan assisted natural draft. A hybrid type that appears like a natural draft though airflow is assisted by a fan

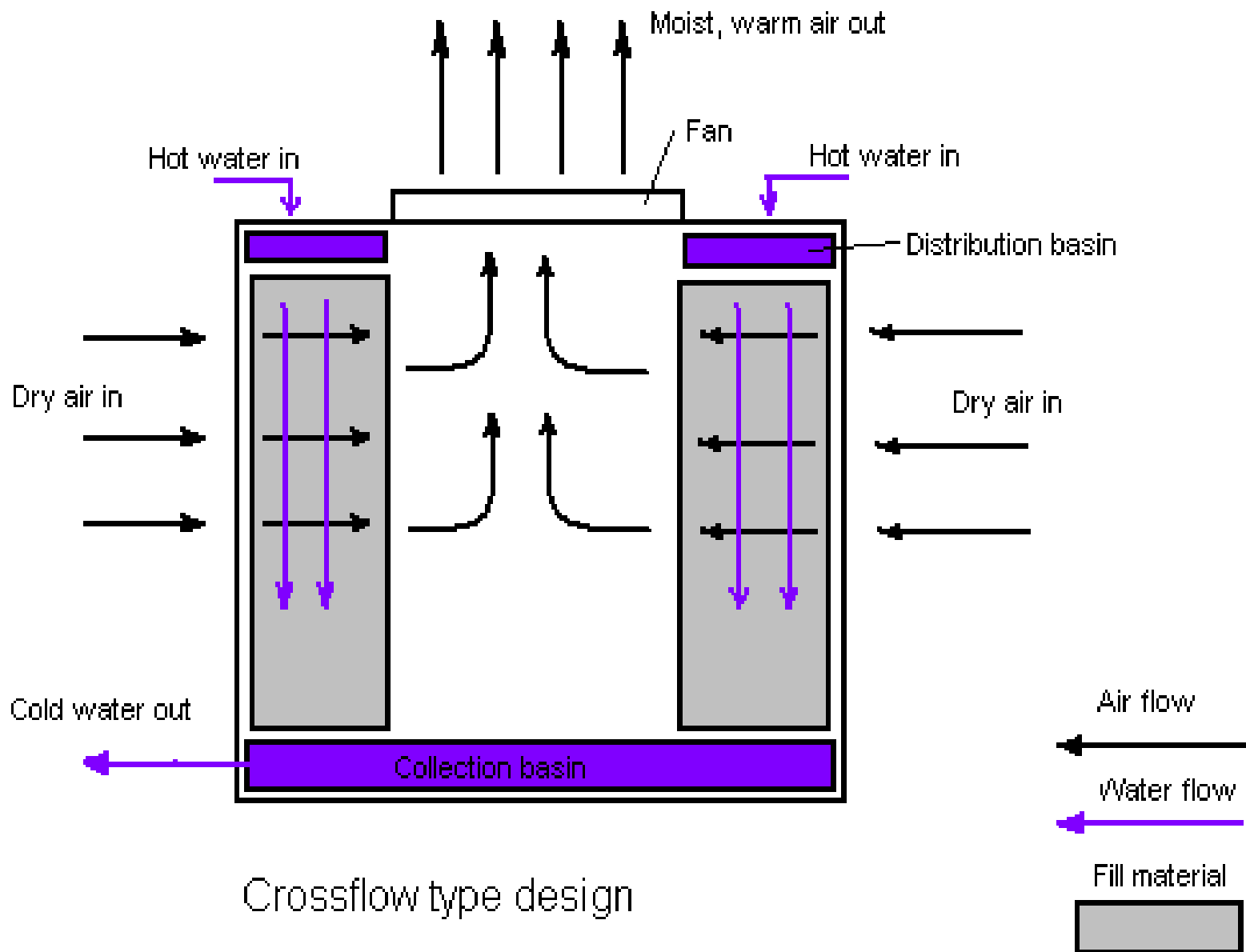
4 - Categorization by air-to-water flow

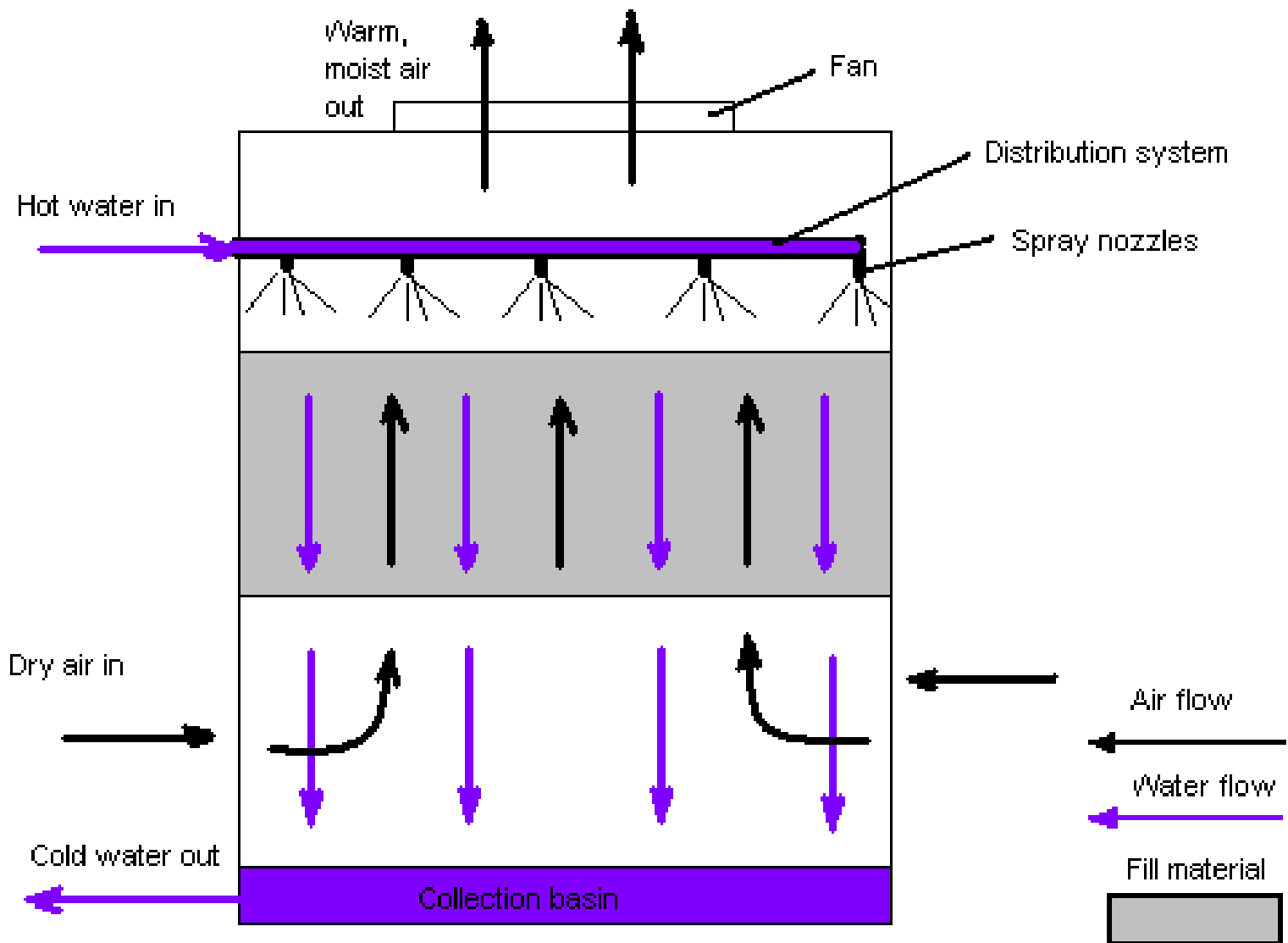
Crossflow

Crossflow is a design in which the air flow is directed perpendicular to the water flow (see diagram below). Air flow enters one or more vertical faces of the cooling tower to meet the fill material. Water flows (perpendicular to the air) through the fill by gravity. The air continues through the fill and thus past the water flow into an open plenum area. A *distribution* or *hot water basin* consisting of a deep pan with holes or *nozzles* in the bottom is utilized in a crossflow tower. Gravity distributes the water through the nozzles uniformly across the fill material

Counterflow

In a counterflow design the air flow is directly opposite to the water flow (see diagram below). Air flow first enters an open area beneath the fill media and is then drawn up vertically. The water is sprayed through pressurized nozzles and flows downward through the fill, opposite to the air flow.





Counterflow type design

Cooling tower fog

Under certain ambient conditions, plumes of water vapor (fog) can be seen rising out of the discharge from a cooling tower (see Image below), and can be mistaken as smoke from a fire. If the outdoor air is at or near saturation, and the tower adds more water to the air, saturated air with liquid water droplets can be discharged—what is seen as fog. This phenomenon typically occurs on cool, humid days, but is rare in many climates

Billowing

Another way of looking into this phenomena is through what is know as “ **BILLOWING** ” . So, what is billowing ?

The working fluid (water) in Rankin cycle flows in a closed cycle loop, and it is re-used continuously. The water vapor with entrained droplets often seen exhausting from power station is actually generated by the cooling system and not from the closed loop Rankin cycle.

The cooling tower operates by using the latent heat of vaporization of the cooling fluid. The white clouds exhausted from the cooling tower are the results of water droplets entrained in the cooling tower air flow, and they are **not**, *as commonly thought*, **steam**. The stream of white clouds is know as **billowing**.

Such billowing stream represent the waste energy heat (vaporization) that could not be converted to useful work in the turbine.

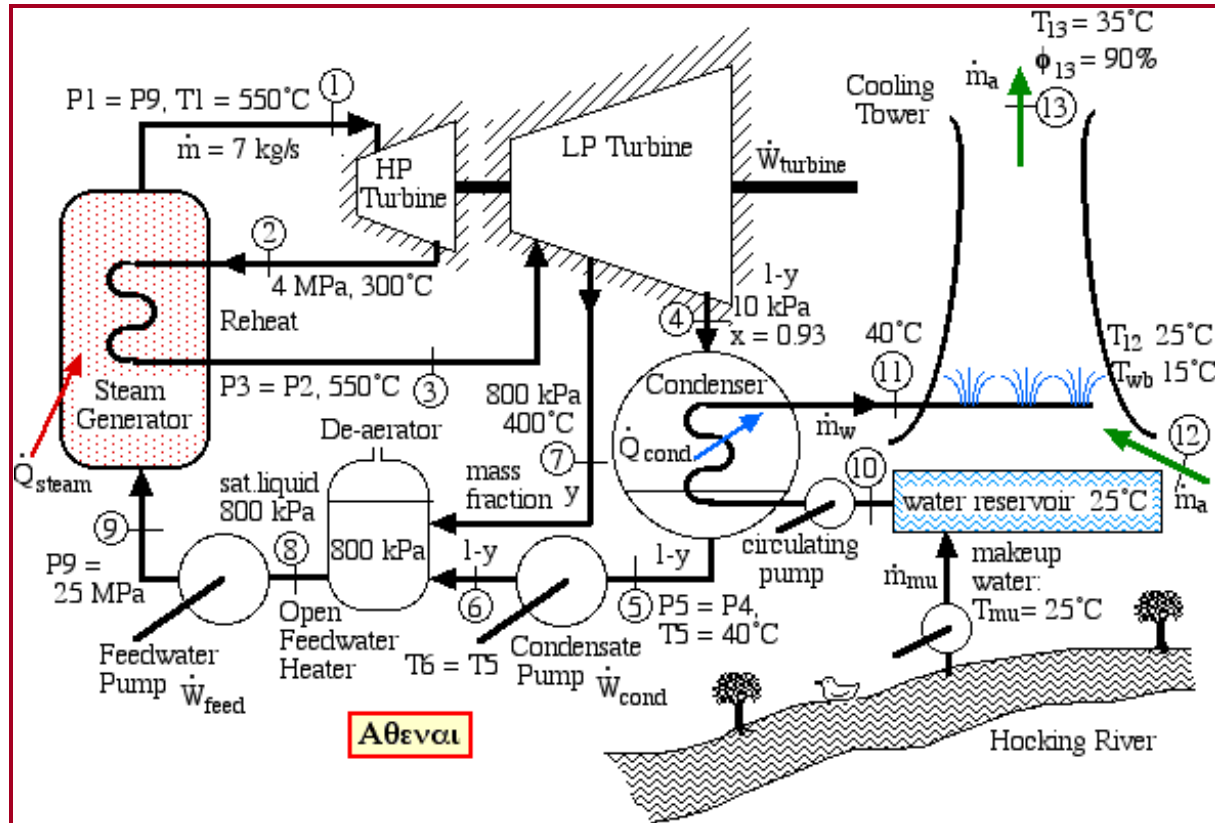


Losses in cooling Towers

- The loss of water in a cooling tower is due to three different reasons and has to be made up during the operation. The **makeup** percentage in modern towers is around **1 %**.
- **Evaporation loss**. A part of the water evaporates, this is what creates the cooling effect. This depends on the ambient temperature and Relative humidity or the ambient wet bulb temperature.
- **Drift loss**. The water particles carried away through the flowing air. Drift eliminators and detail design have reduced this largely. In modern towers, this could be in the range of 0.02 % of the water flow.
- **Blowdown losses**. The evaporated water leaves behind the salts, which over time accumulates increasing the TDS levels. This requires to be blowdown occasionally. This constitutes a loss which has to be made up.

Tutorial

Recall [Problem 4.2](#), in which we analysed a Supercritical Steam Power Plant with Reheat and an Open Feedwater Heater/De-aerator to service about 10,000 households in Athens, Ohio. The City Council was somewhat perturbed about the possible thermal pollution of the Hocking River and have requested that we evaluate the use of a Cooling Tower in order to cool the condenser fluid stream, rather than direct cooling by the Hocking River, with only the makeup water being supplied by the river. For purposes of this exercise we have chosen the additional parameters associated with the Cooling Tower as shown in the diagram below.



We found in [Problem 4.2](#) that the power required to cool the steam in the condenser is 12.9 MW. Furthermore since we are not returning the water to the Hocking River we no longer have the restriction of a 10°C maximum water temperature increase. We have chosen a temperature of 40°C at station (11) in order to ensure cooling since from the [steam tables](#) we find that the saturation temperature at 10 kPa is 45.8°C . In this problem we wish to evaluate the performance and suitability of this proposed design.

Chapter two

steam power plant

2.06 - Industrial water treatment

introduction

- **Industrial Water Treatment** can be classified into the following categories:
- Boiler water treatment
- Cooling water treatment
- Wastewater treatment
- Water treatment is used to optimize most water-based industrial processes, such as: heating, cooling, processing, cleaning, , so that operating costs and risks are reduced. Poor water treatment lets water interact with the surfaces of pipes and vessels which contain it.

Power plant

- Boilers feed water needs to be as pure as possible with a minimum of suspended solids and dissolved impurities which cause corrosion . Steam boilers can scale up or corrode, and these deposits will mean more fuel is needed to heat the same amount of water.
- Cooling towers can also scale up and corrode, but left untreated, the warm, dirty water they can contain will encourage bacteria to grow, and Legionnaires' Disease can be the fatal consequence

advantages

- In many cases, effluent water from one process might be perfectly suitable for reuse in another process somewhere else on site. With the proper treatment, a significant proportion of industrial on-site wastewater might be reusable. This can save money in three ways:
 - 1- lower charges for lower water consumption,
 - 2- lower charges for the smaller volume of effluent water discharged and
 - 3- lower energy costs due to the recovery of heat in recycled wastewater.

objectives

- Industrial water treatment seeks to manage four main problem areas:
- scaling,
- corrosion,
- microbiological activity and
- disposal of residual wastewater.
- Boilers do not have many problems with microbes as the high temperatures prevents their growth

Scaling

- Scaling occurs when the chemistry and temperature conditions are such that the dissolved mineral salts in the water are caused to precipitate and form solid deposits. These can be mobile, like a fine silt, or can build up in layers on the metal surfaces of the systems. Scale is a problem because :
- 1- it **insulates** and heat exchange becomes less efficient as the scale thickens, which wastes energy.
- 2- it **narrows** pipe widths and therefore increases the energy used in pumping the water through the pipes.

Corrosion

- Corrosion occurs when the parent metal oxidizes (as iron rusts, for example) and gradually the integrity of the plant equipment is compromised. The corrosion products can cause similar problems to scale, but corrosion can also lead to leaks, which in a pressurized system can lead to catastrophic failures.

Microbes

- Microbes can thrive in untreated cooling water, which is warm and sometimes full of organic nutrients, as wet cooling towers are very efficient air scrubbers. Dust, flies, grass, fungal spores and so on collect in the water and create a sort of "microbial soup" if not treated with biocides. Most outbreaks of the deadly Legionnaires' Disease have been traced to unmanaged cooling towers

Disposal of residual industrial wastewaters

- Disposal of residual wastewaters from an industrial plant is a difficult and costly problem. Most petroleum refineries, chemical and petrochemical plants have onsite facilities to treat their wastewaters so that the pollutant concentrations in the treated wastewater comply with the local and/or national regulations regarding disposal of wastewaters into community treatment plants or into rivers, lakes or oceans.

Methods of Water treatment

- The treatment of raw water (natural water) can be done in various methods , and the
- followings are briefly explained :
- **1- mechanical treatment.**
- Settling, filtering, and trapping are simple methods of removing suspended solids.
- **2- chemical treatment.**
- For removing hardness by replacing the iron, calcium, and magnesium ions (hard-
- water) by sodium ions .
- **3- cation exchange.**
- Positive charge metal ions exchange for removing residual hardness.
- **4- demineralization.**
- For removing dissolved solids (distillation), since boilers operates at high pressure, Water evaporates and then condenses leaving solids behind

Chapter two

steam power plant

2.07 - Power Plant process evaluation & assessment

introduction

- There are two methods of such evaluation in actual sense, as evaluation of power
- plant process is evaluating the plant main components , i.e the boiler and the
- turbine.
- The main parameters that shows how good the power plant operates are :
- 1- the level of the turbine mechanical output available for the electrical generator
- to generate and produce electricity.
- 2- the level of the boiler utilizes the fuel heat energy to produce enough steam at
- proper pressure and temperature to operate the turbine.
- Therefore, the efficiencies of these components to operate, and thus the heat energy
- transferred from components to components represent a good picture of how well
- the plant is operating .
- The two methods of plant evaluation and assessment are :
- i- efficiencies.
- ii- heat rate

I – Efficiencies

- 1- cycle ideal efficiency (Rankine)
- $\eta_R = (\text{net work o/p}) / (\text{heat supplied by boiler})$
- $= (h_1 - h_2) / (h_1 - h_4)$

- 2 – turbine efficiency (η_T)
- $\eta_T = (\text{actual } \Delta h) / (\text{ideal } \Delta h)$
- $= (h_1 - h_{2'}) / (h_1 - h_2)$
- Where
- $1 \rightarrow 2$: ideal expansion $\rightarrow S1 = S2$
reversible
- $1 \rightarrow 2'$: actual expansion $\rightarrow S2' = S2$
irreversible

- 3 – boiler efficiency (η_B)
- for unit mass rate
- $\eta_B = (h_1 - h_{fw}) / (m_f \cdot HHV)$
- for a given mass rate
- $\eta_B = (m_s \cdot \Delta h) / (m_f \cdot HHV).$
- $= (m_s \cdot \Delta h_b) + (m_{rht} \cdot \Delta h_{rht}) / (m_f \cdot$
- $HHV)$ with reheat

II – Heat Rate

- 1 – (turbine – cycle) heat rate TCHR
- This is defined as the heat required to be supplied to the steam per KWhr of electric Power output.
- $TCHR = (\text{heat supplied to turbine cycle} / \text{time}) / (\text{gross generator output kw})$
- $\quad = (Q_T) / (P_{GO})$
- $P_{GO} = W_a \cdot \eta_G$
- $W_a = \text{actual work done by the turbine}$
- $\eta_G = \text{electric generator efficiency}$
- $\quad = (\text{electric power produced}) /$
- $\quad (\text{mechanical power supplied})$

- However, the actual mechanical power supplied by the turbine is related to the turbine ability to utilize the thermal energy available from the boiler, such turbine ability means turbine efficiency, therefore
- $W_a = \eta_T (\eta_{th} \cdot Q_T)$
- $TCHR = 1 / (\eta_T \cdot \eta_G \cdot \eta_{th})$

- 2 – (Boiler-Turbine) heat rate **BTHR**
- **BTHR = $Q_T / (\eta_B \cdot P_{Go})$**
- Where η_B is the boiler efficiency

- 3 – Overall power plant heat rate OPPHR
- This is defined as the heat required to be supplied to the power plant in the form of a basic fuel per unit KWhr of power output from the plant.
- $OPPHR = (\text{heat available from fuel} / \text{time}) / (P_{GO} (1 - (P_{ax} / P_{GO})))$
-
- $= Q_F / (P_{GO} (1 - (P_{ax} / P_{GO})))$
- Where P_{ax} power consumed by auxiliary at site.
- But,
- Heat supplied to turbine / time $= \eta_B (\text{heat available from fuel} / \text{time})$
- i.e ,
- $Q_T = \eta_B \cdot Q_F$
- $Q_F = Q_T / \eta_B$
- $OPPHR = (Q_T / \eta_B) / (P_{GO} (1 - (P_{ax} / P_{GO})))$
- $= Q_T / (\eta_B \cdot P_{GO} (1 - (P_{ax} / P_{GO})))$

Chapter Three

GAS TURBINE POWER PLANT

3.1 - Introduction

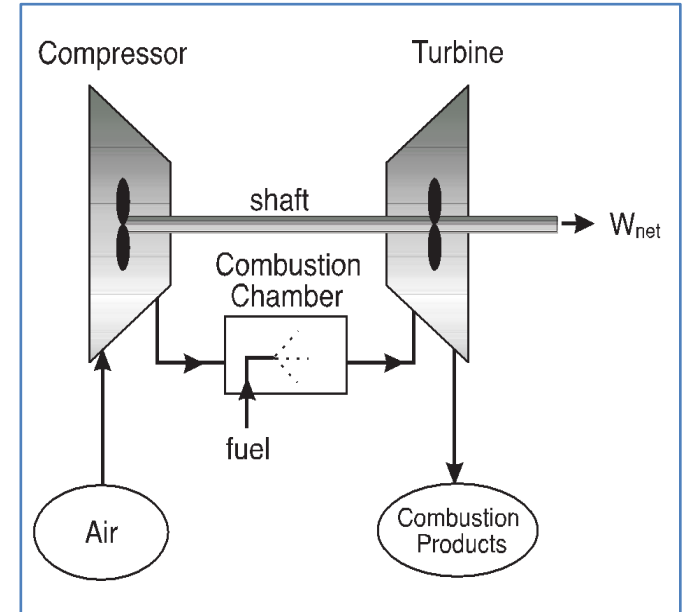
1 – Introduction

The **gas turbine** in such plant obtains its power by utilizing the heat energy from the burnt gases in the **combustion chamber**, inside which fuel and air combustion process takes place.

The burnt gases are at high temperature and high pressure expands in the **turbine** through a series of “ **fixed & moving blades** ” in exactly **similar** operation as in the **steam power plant** .

The simplest form of the gas turbine power plant consist of three main components:

- i – **compressor**. (C)
- ii – **combustion chamber** (CC)
- iii – **turbine** (T)



The **compressor** is , either a **centrifugal or axial type**, is coupled with the turbine by the **driving shaft**, i.e the compressor is driven by the turbine, and so compresses the working fluid to a high pressure ranging between (15–20 bars).

Under such compression process, assuming **no losses** in both turbine and compressor, the power developed by the turbine would **just equal** to the power consumed by the compressor, and the **net work** output would then be **zero** .

To obtain useful outcome from the system, another component is necessary , where the working fluid (WF) volume and pressure can be interrelated as follows :

I – WF volume may be increased at constant pressure. (**diesel cycle**)

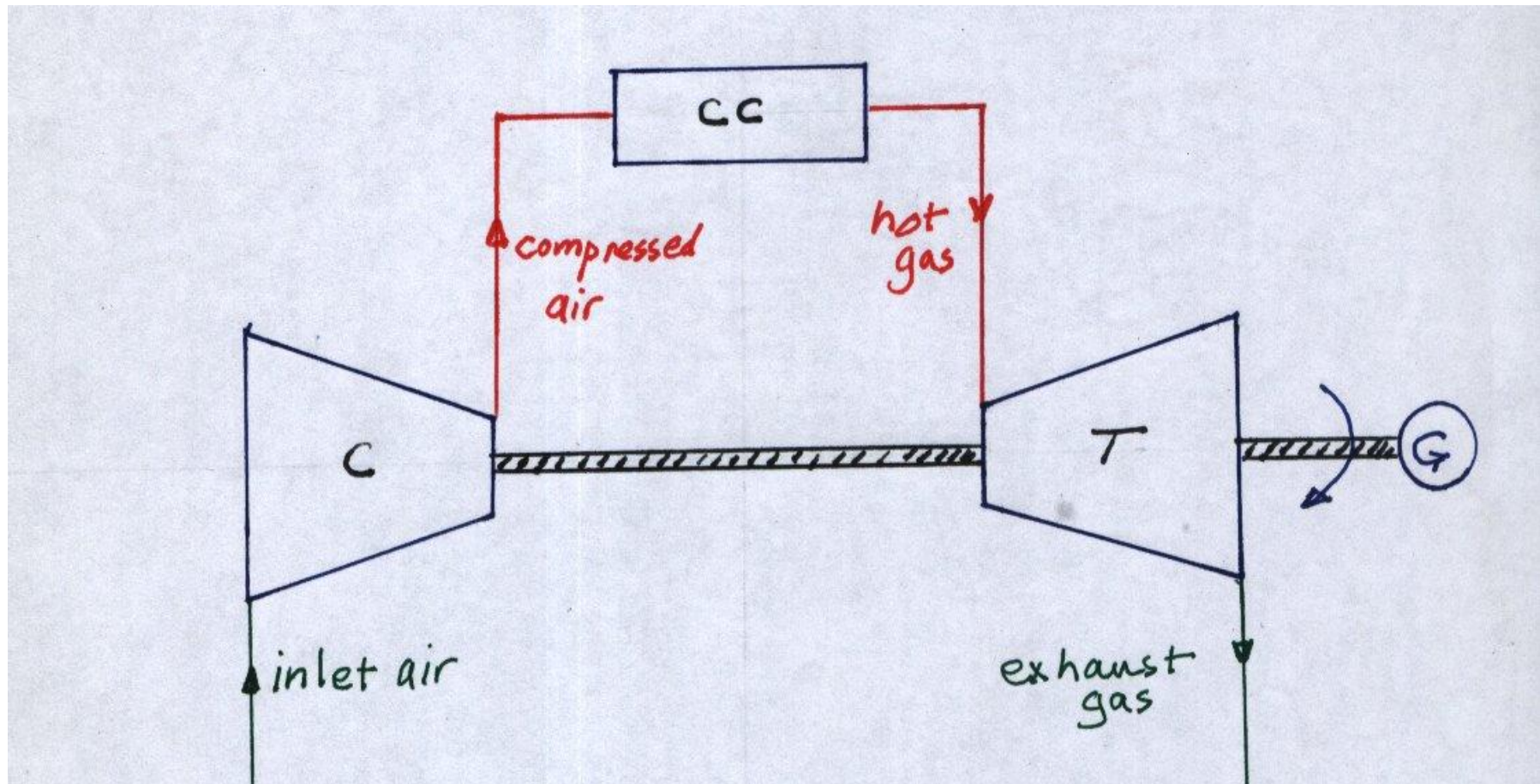
II – WF pressure may be increased at constant volume. (**otto cycle**).

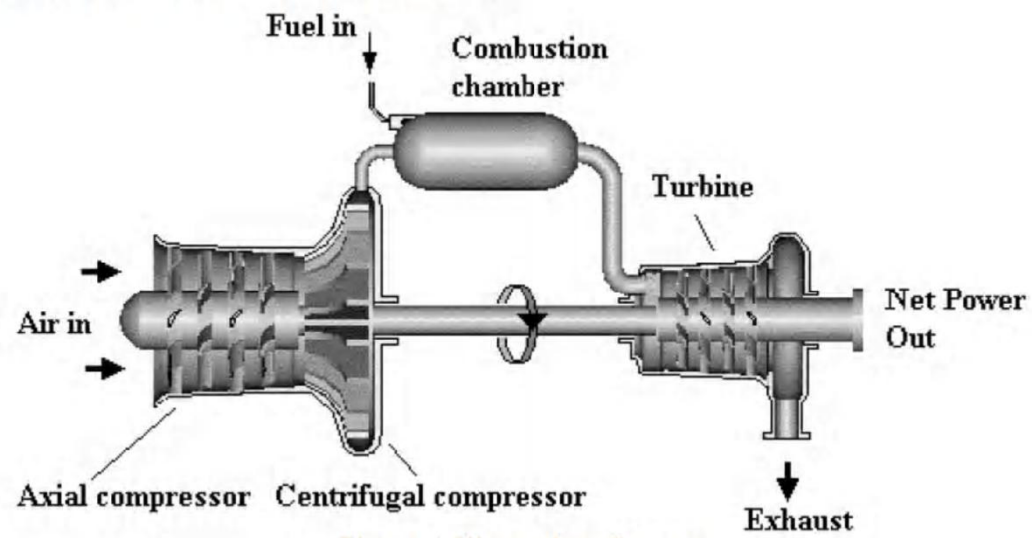
This can be achieved by **heat addition** either under constant pressure according to the theoretical **diesel cycle**, or under constant volume according to the theoretical **otto cycle** , where under both conditions the WF temperature will be raised.

This can be achieved by adding a **combustion chamber** to the system.

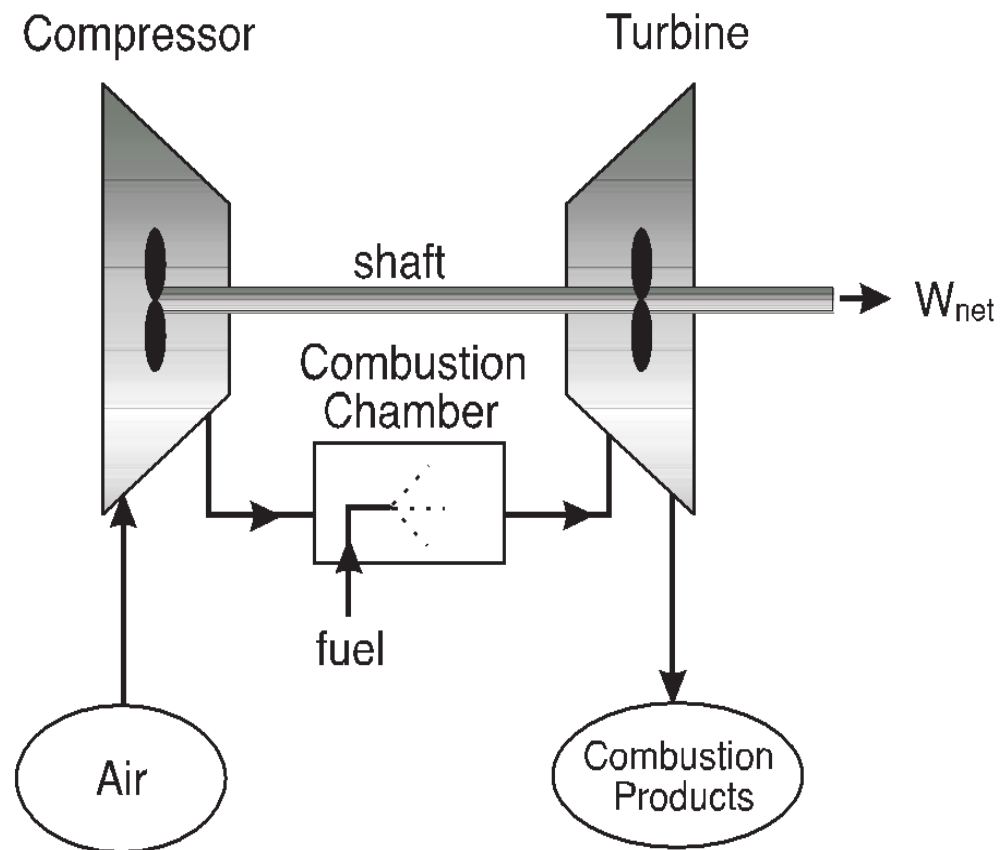
Therefore, this simple system can be illustrated as in (fig. 1) .

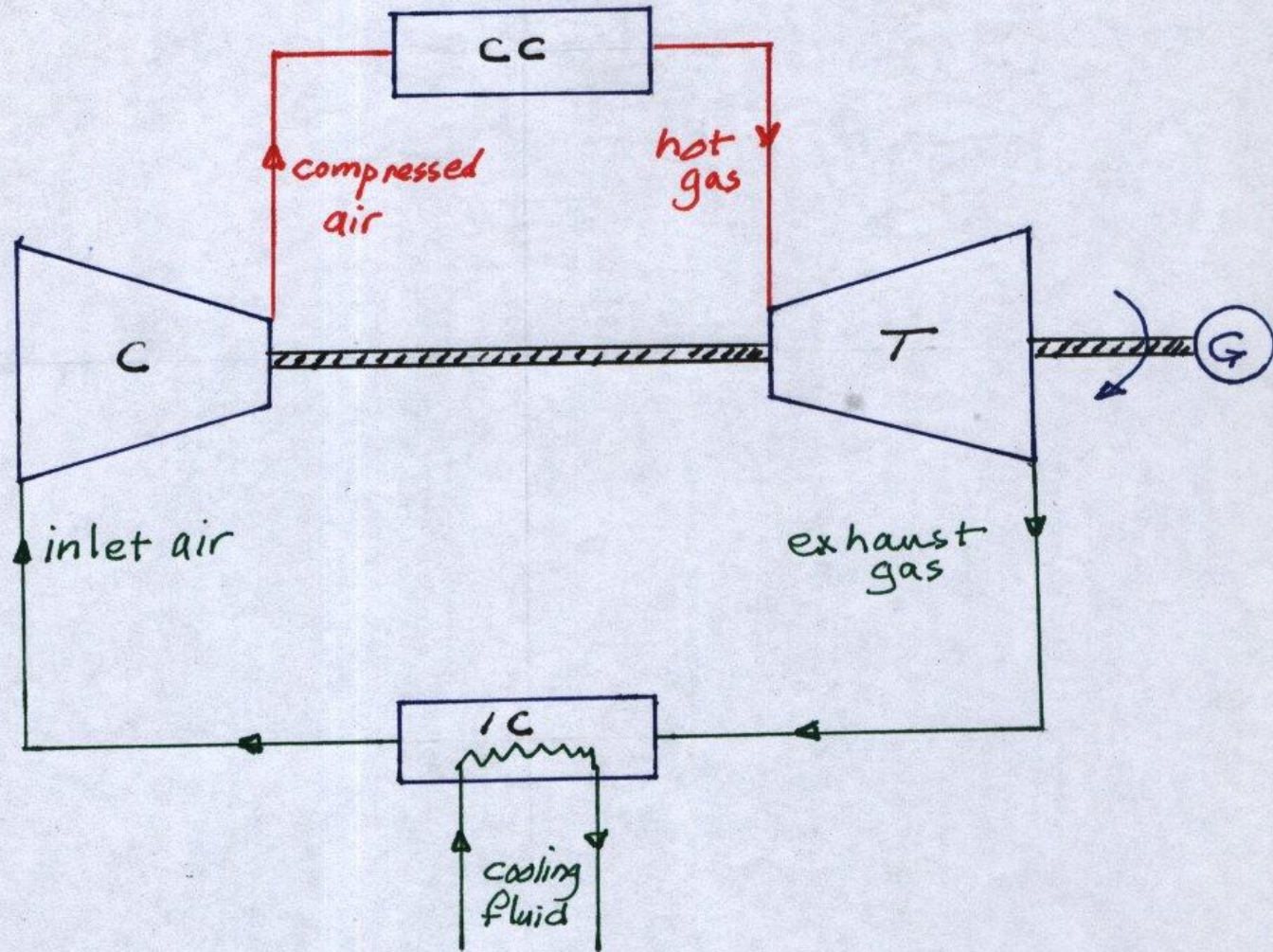
Fig. 1



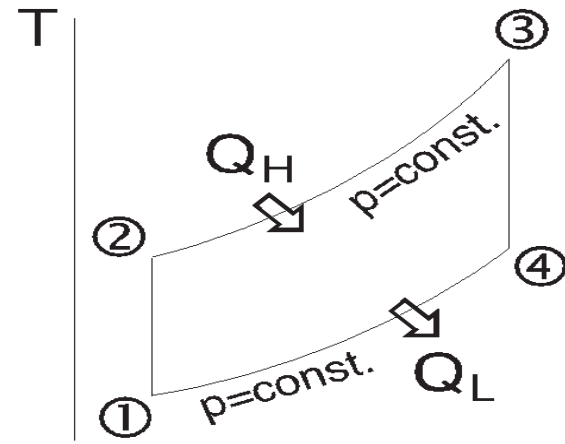
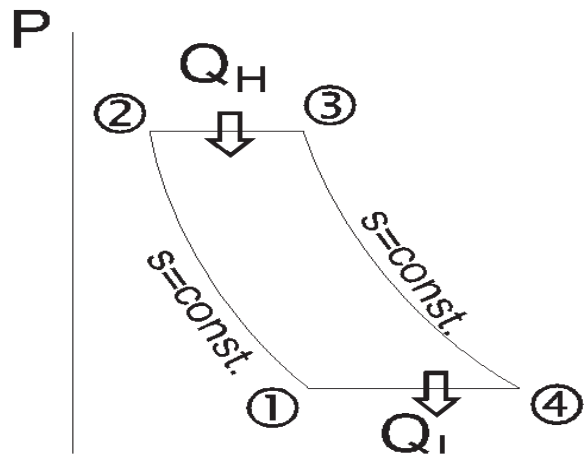
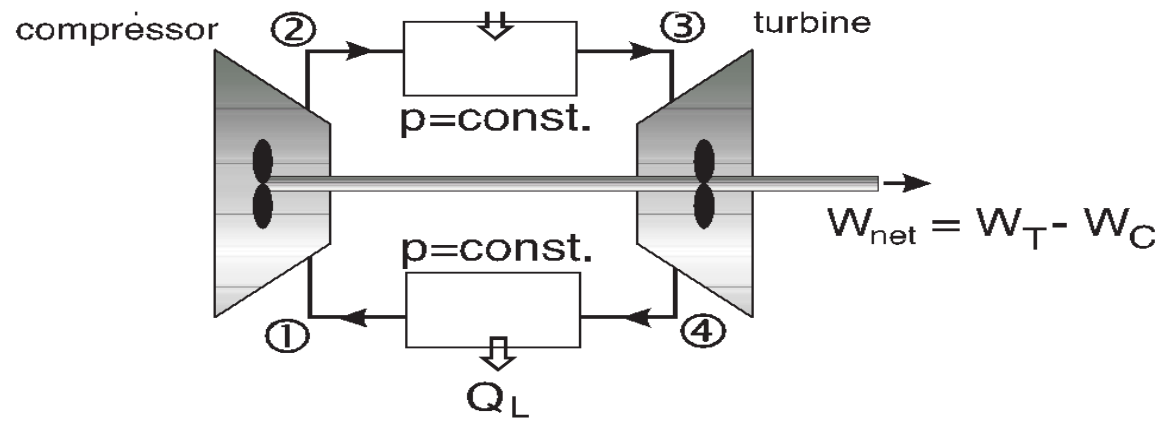


Open Cycle Gas Turbine Engines





===



- 1- compressor [C]
 - 2- Combustion chamber [CC]
 - 3- Turbine [T]
 - 4- Generator [G]
 - 5- Inter cooler [IC]
- open
sys.

closed
sys

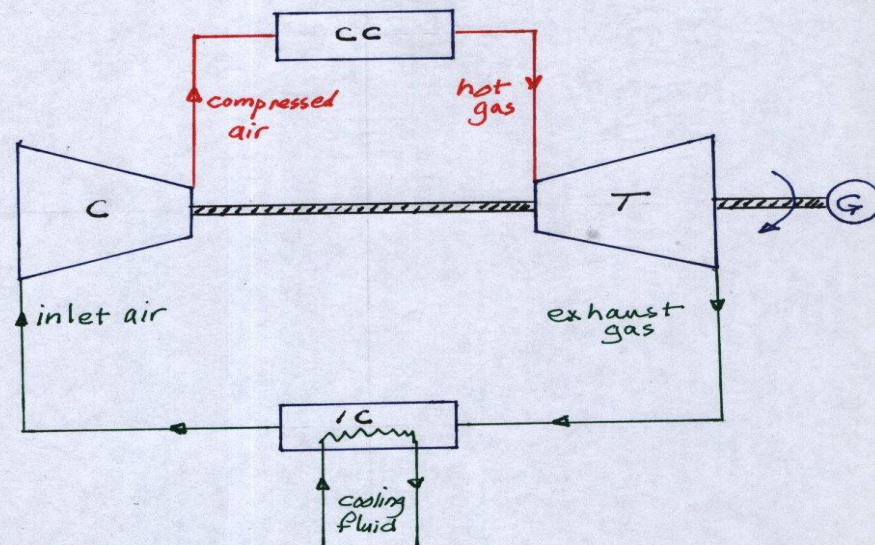


Fig. 1

1 - as the compressor is coupled to the turbine, and thus absorb some of the power produced by the turbine , then the system power production can be shown as follows :
$$\text{net work} = (\text{work produced by the turbine}) - (\text{work absorbed by the compressor})$$
$$NW = W_t - W_c$$

2 - More than Fifty percent of the energy converted is used by the compressor. Only around 35 % of the energy input is available for electric power generation in the generator. The rest of the energy is lost as heat of the exhaust gases to the atmosphere.

3 – the fuel used can be any of the following :

- i - fuel oil
- ii - natural gas
- iii- coal gas
- iv- producer gas
- v - blast furnace gas
- vi- pulverized coal

R
E
M
A
R
K
S

4 - Three parameters that affect the performance of a gas turbine are

- The pressure of the air leaving the compressor.
- The hot gas temperature leaving the Combustion chamber.
- The gas temperature of the exhaust gases leaving the turbine

5 – open & closed cycle

The system operation can be one of the followings :

- i – open cycle – induction & exhausting from & to the atmosphere.
- ii – closed cycle – using the same recycled WF with-out atmospheric direct connection.

6 – start – up

Means of external source of power is required to start the system operation, such as prime-mover, electrical starter motoretc., as compression process is essential for the commencement of the cycle.

Gas Turbine **power plant classification**

There are several parameters used to classify different types of gas turbine power plant. Generally such parameters are commonly agreed upon in almost all engineering institutions worldwide:

1 - Working cycle

- i – open cycle
- ii – closed cycle

2 – shaft power out put

- i– single shaft system
- ii – two shafts system

3 – turbines

- i – single turbine
- ii – multi turbine.

4 – compressors

- i – single compressor
- ii – multi compressor

5 – combustion chamber

- i – single Combustion Chamber
- ii – two Combustion Chamber

6 – working fluid flow

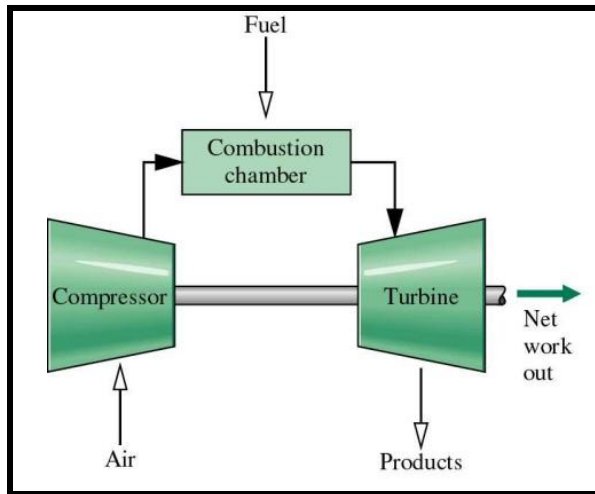
- i – multi turbine in series
- ii – multi turbine in parallel

7 – application

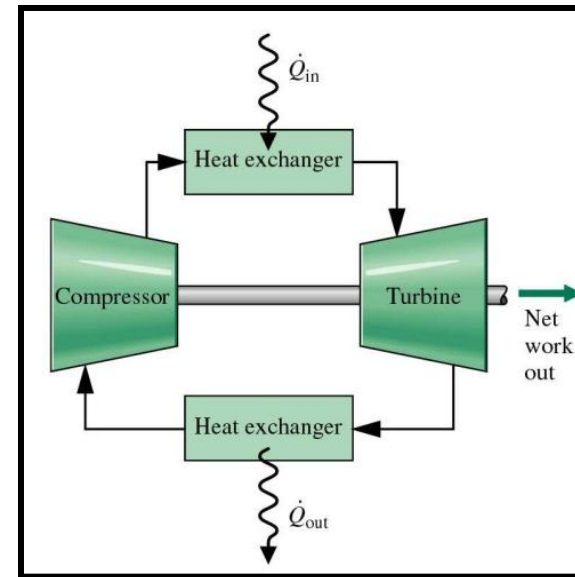
- i – electric power generation
- ii – jet propulsion
- iii – turbo-prop generation
- iv – industrial power generation

1 - Working cycle

i – open cycle



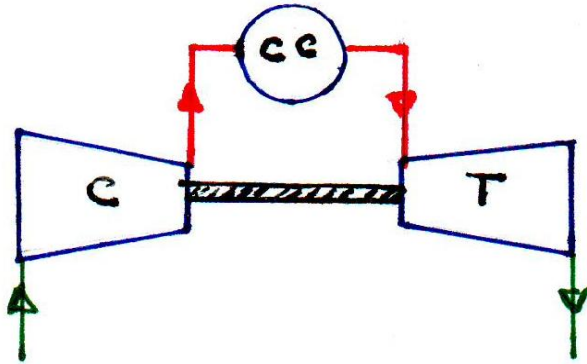
ii – closed cycle



Both cycles requires means of external source of power to start the system operation, such as prime movers, electric starter motor, or other means which is necessary to start compression and induction. See hand-outs for more details.

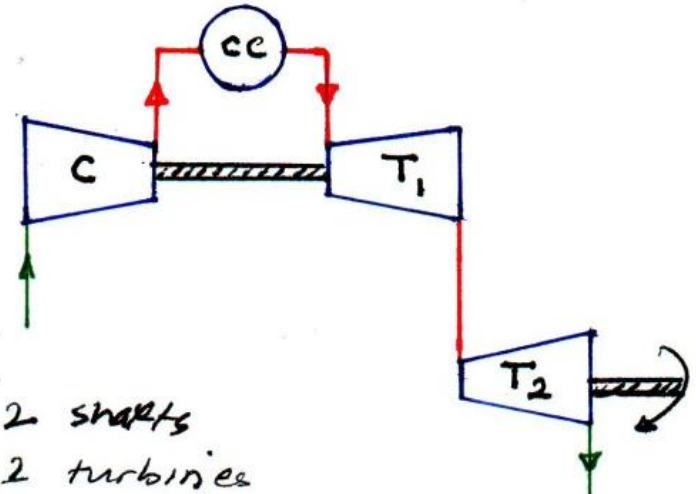
2 – shaft power out put

i – single shaft system



single shaft

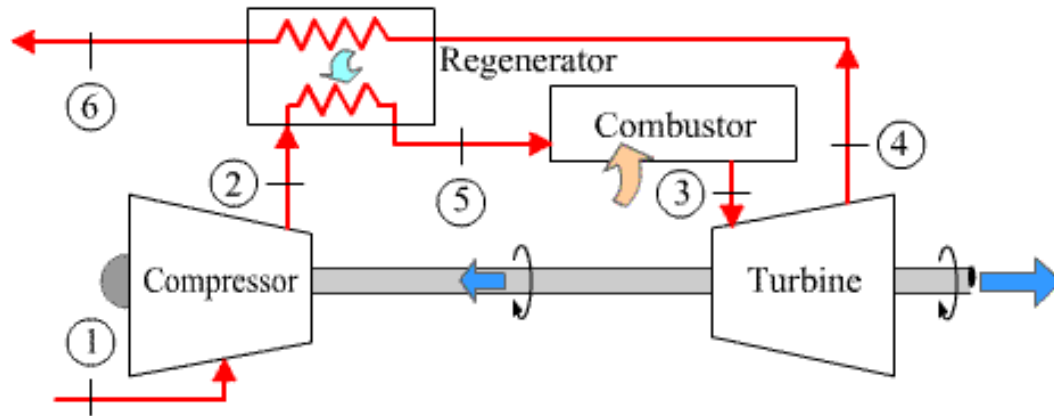
ii – two shafts system



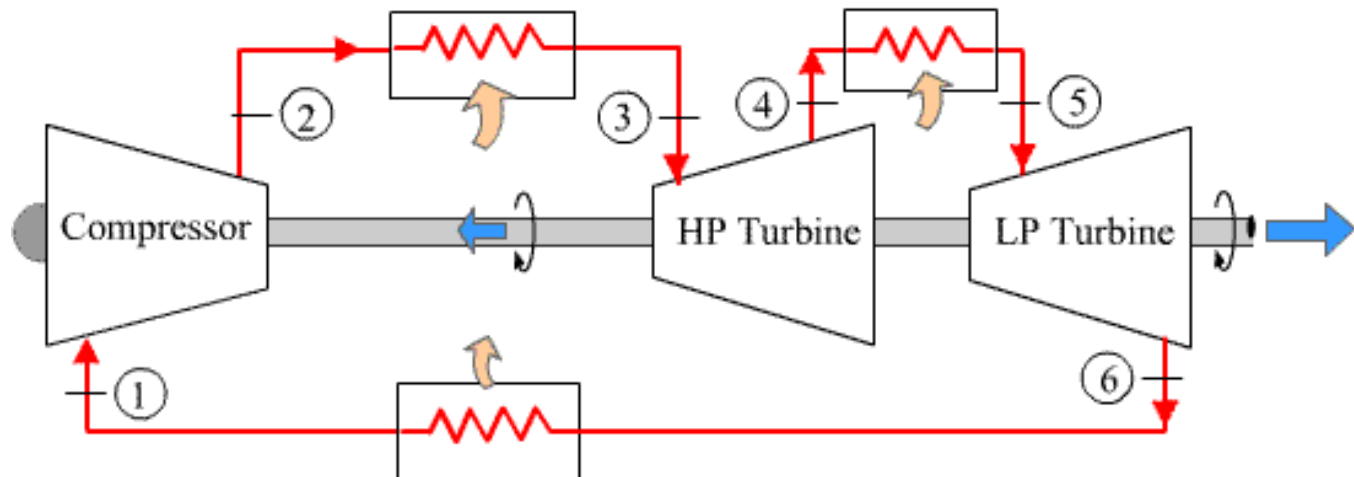
2 shafts
2 turbines

3 – turbines

i – single turbine

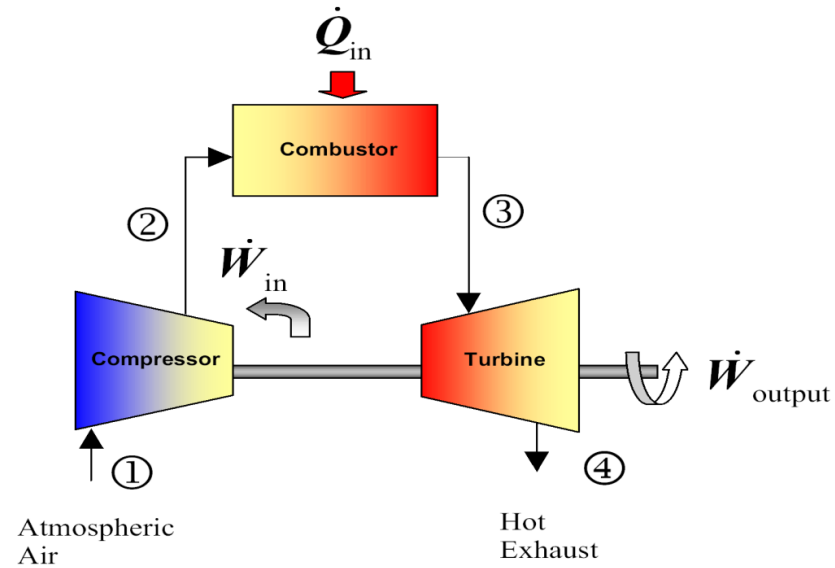


ii – multi turbine

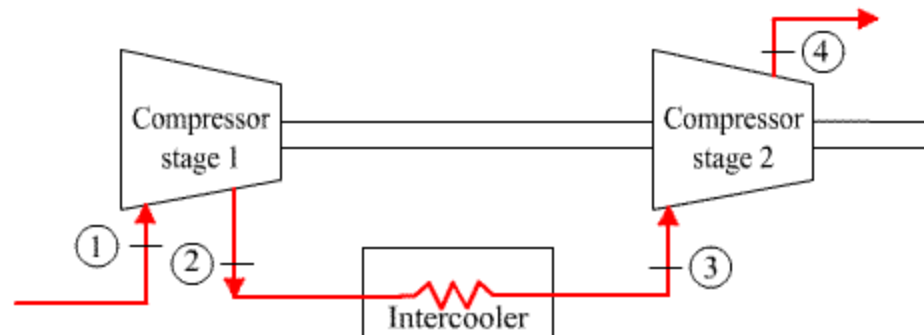


4 – compressors

i – single compressor

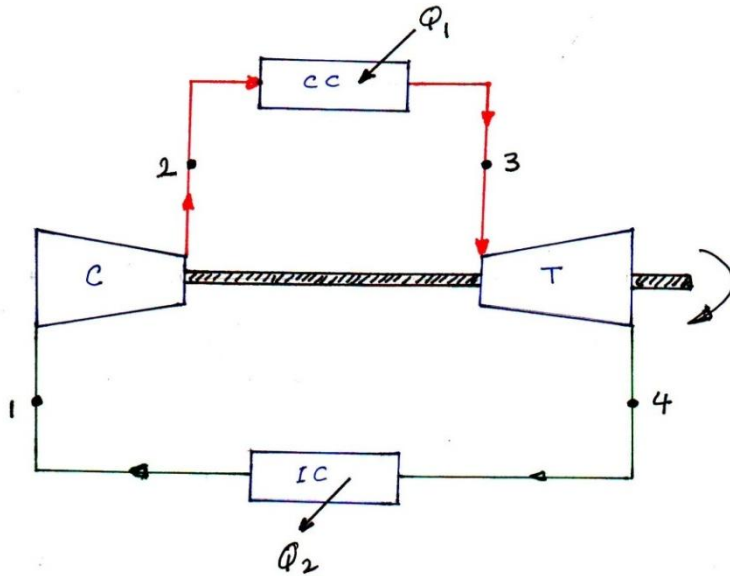


ii – multi compressor

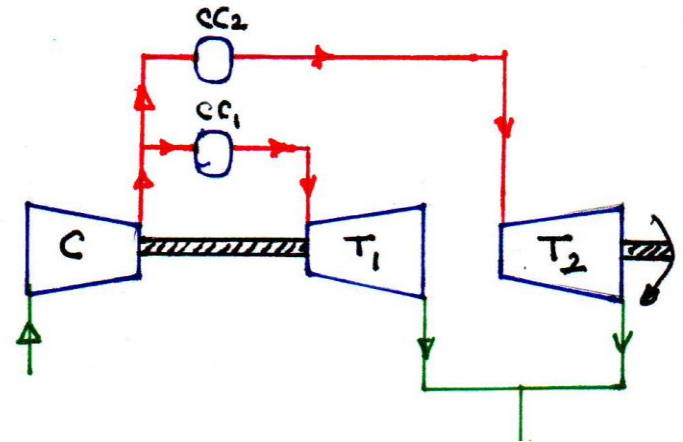


5 – combustion chamber

i – single Combustion Chamber

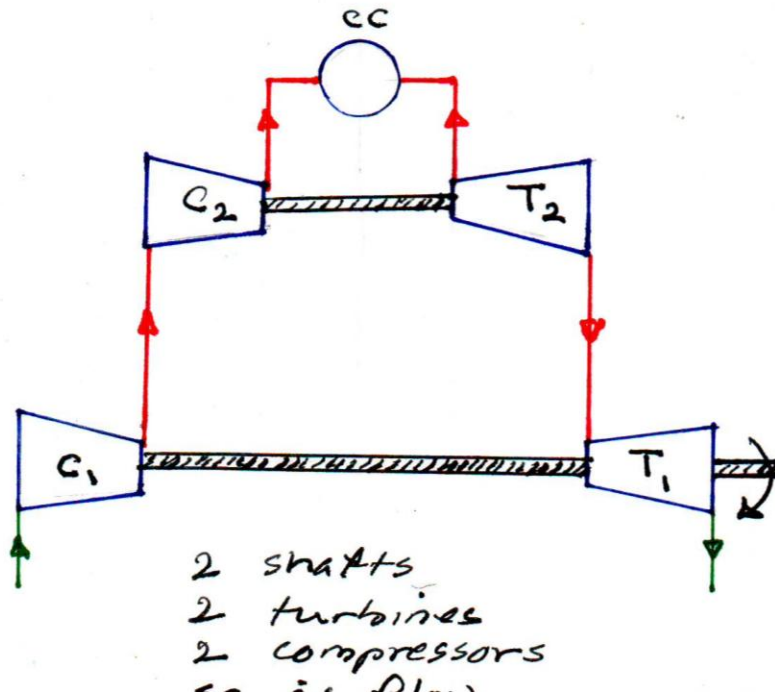


ii – two Combustion Chamber

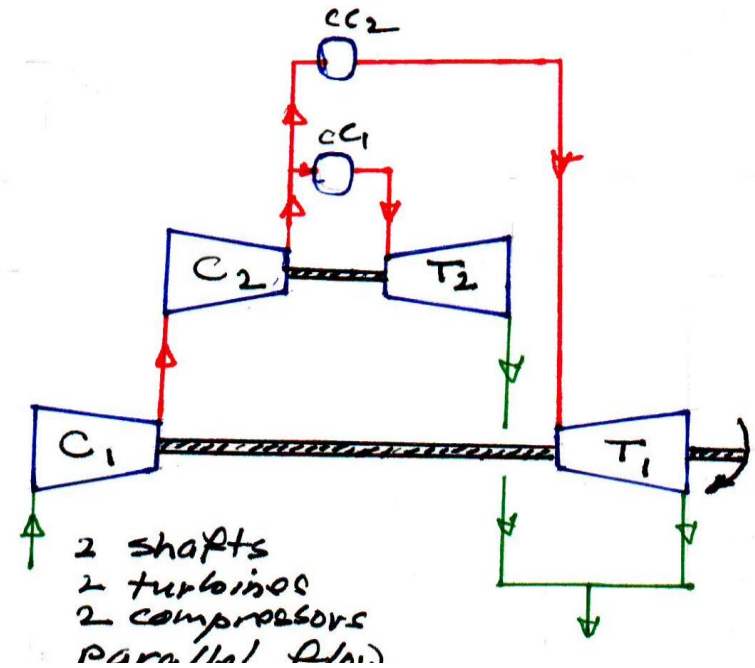


6 – working fluid flow

i – multi turbine in series

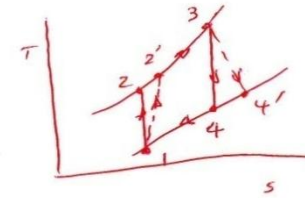
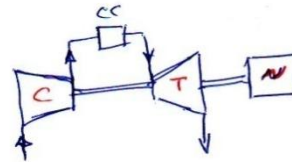


ii – multi turbine in parallel

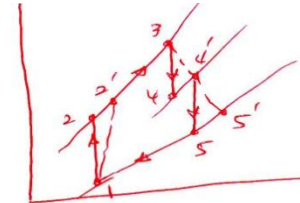
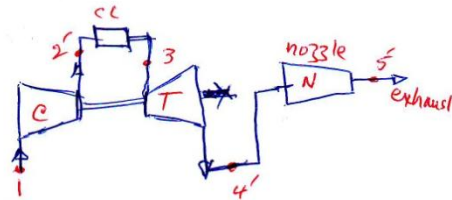


7 – application

i – electric power generation

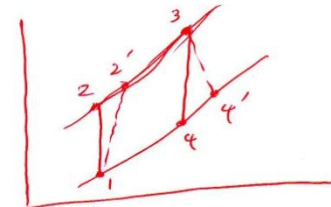
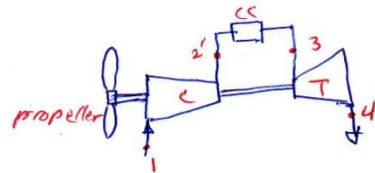


ii – jet propulsion



the nozzle is the propulsion nozzle.
the aircraft is powered by the reactive thrust of the jet of gases leaving the nozzle

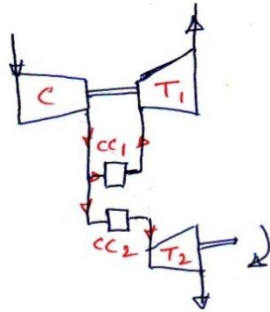
iii – turbo-prop generation



net work available to drive the propeller is

$$= C_p (T_3 - T_{4'}) - C_p (T_{2'} - T_1)$$

iv – industrial power generation



The compressed air is splitted into 2 streams ,

i, one to $CC_1 \rightarrow T_1$ to drive compressor

ii one to $CC_2 \rightarrow T_2$ to drive power turbine

i.e T_1 : compressor turbine

T_2 : power turbine

This arrangement is also called "parallel flow" unit

Chapter Three

GAS TURBINE POWER PLANT

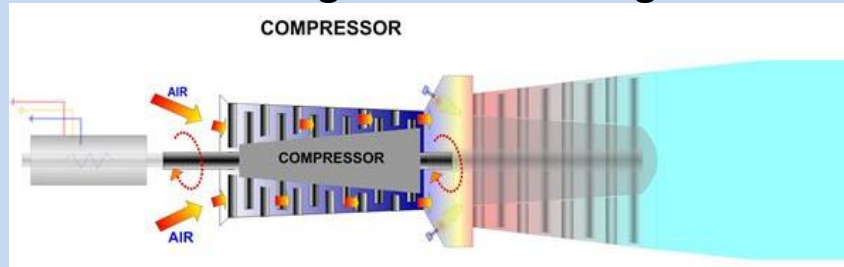
3.2 How does a Gas Turbine Power Plant Work

I - The Main Equipment.

- Gas turbine functions in the same way as the Internal Combustion engine. It sucks in air from the atmosphere, compresses it. The fuel is injected and ignited. The gases expand doing work and finally exhausts outside. The only difference is instead of the reciprocating motion, gas turbine uses a rotary motion throughout.
- The main components of such system can be briefed as below :

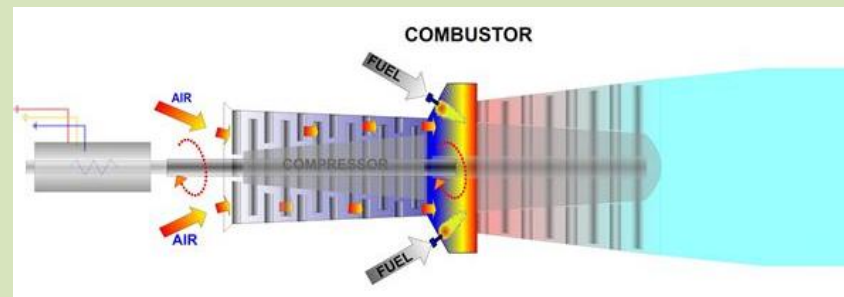
1. Compressor.

The compressor sucks in air from the atmosphere and compresses it to pressures in the range of 15 to 20 bar. The compressor consists of a number of rows of blades mounted on a shaft. This is something like a series of fans placed one after the other. The pressurized air from the first row is further pressurized in the second row and so on. Stationary vanes between each of the blade rows guide the air flow from one section to the next section. The shaft is connected and rotates along with the main gas turbine.



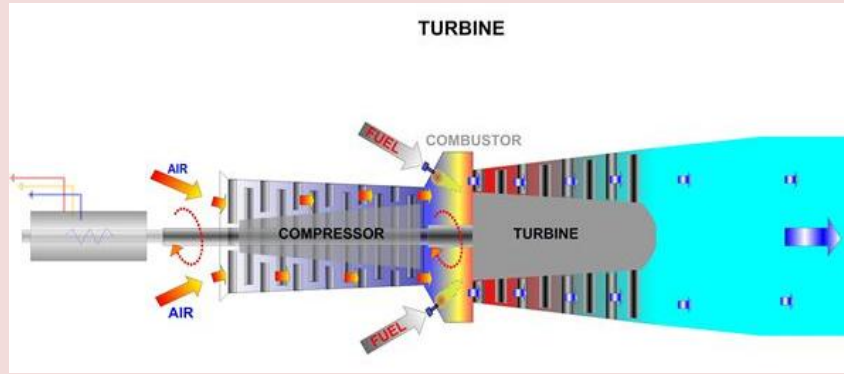
2. Combustor.

This is an annular chamber where the fuel burns and is similar to the furnace in a boiler. The air from the compressor is the combustion air. Burners arranged circumferentially on the annular chamber control the fuel entry to the chamber. The hot gases in the range of 1400 to 1500 °C leave the chamber with high energy levels. The chamber and subsequent sections are made of special alloys and designs that can withstand this high temperature.



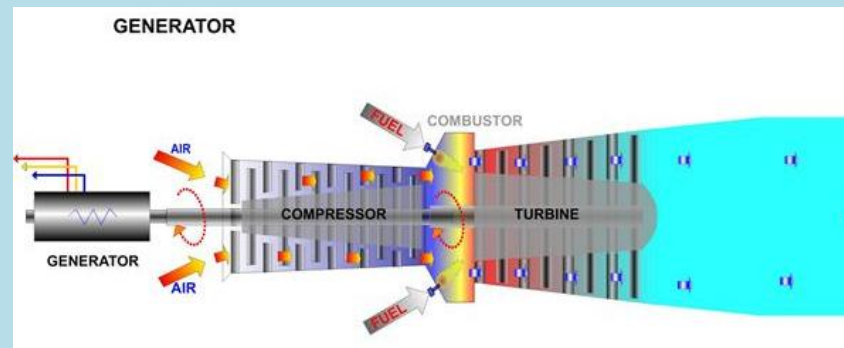
3. Turbine

The turbine does the main work of energy conversion. The turbine portion also consists of rows of blades fixed to the shaft. Stationary guide vanes direct the gases to the next set of blades. The kinetic energy of the hot gases impacting on the blades rotates the blades and the shaft. The blades and vanes are made of special alloys and designs that can withstand the very high temperature gas. The exhaust gases then exit to exhaust system through the diffuser. The gas temperature leaving the Turbine is in the range of 500 to 550 °C.



4 . generator

The gas turbine shaft connects to the generator to produce [electric](#) power. This is similar to generators used in conventional thermal power plants.



II - The Auxiliary Systems.

- The three main sections of a Gas Turbine are the Compressor, Combustor and Turbine. The gas turbine power plant has to work continuously for long period of time without **output and performance decline**. Apart from the main sections there are other important auxiliaries systems which are required for operating a Gas Turbine Power Plant on a long term basis.

1-Air Intake System

- Air Intake System provides clean air into the compressor. During continuous operation the impurities and dust in the air deposits on the compressor blades. This reduces the efficiency and output of the plant . The **Air Filter** in the Air Intake system prevents this.
- A blade cleaning system comprising of a high pressure pump provides on line **cleaning facility** for the compressor blades.
- The flow of the large amount of air into the compressor creates high noise levels. A **Silencer** in the intake duct reduces the noise to acceptable levels.

2-Exhaust System

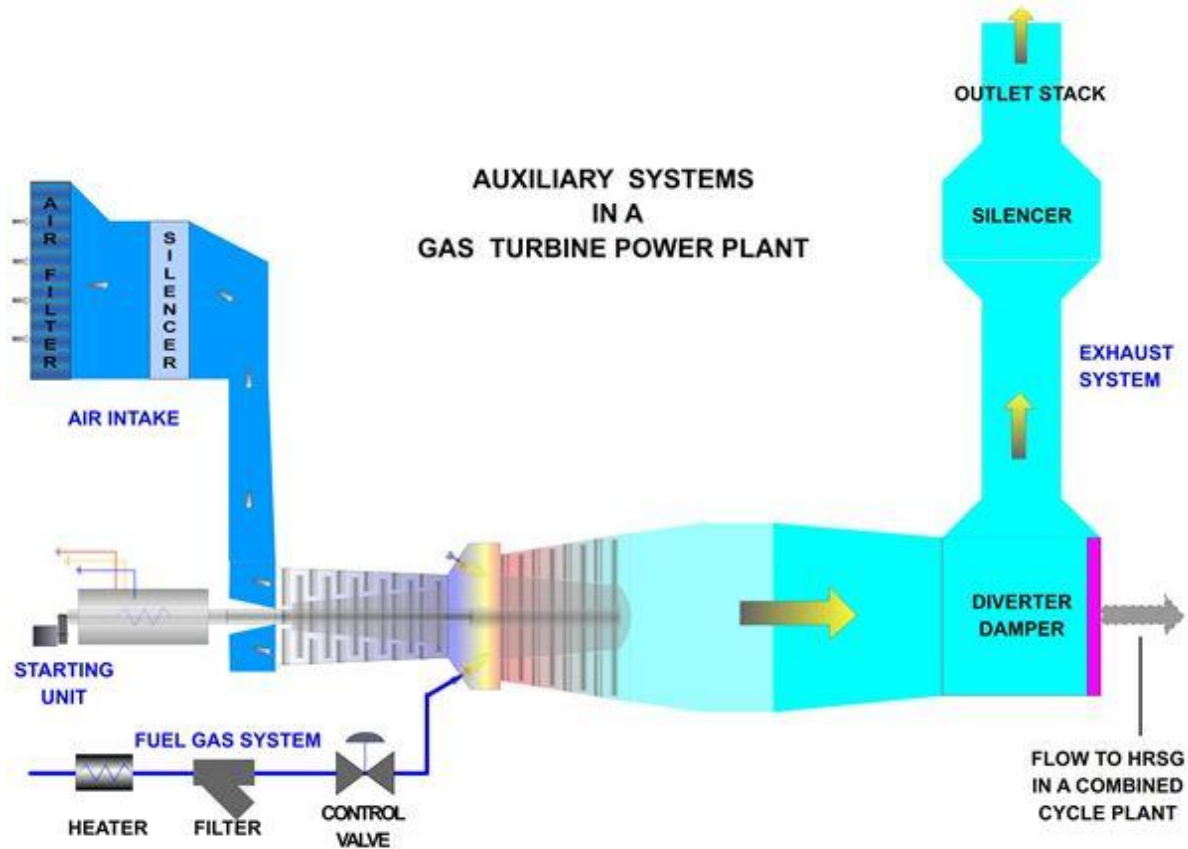
- Exhaust system discharges the hot gases to a level which is safe for the people and the environment. The exhaust gas that leaves the turbine is around 550 °C. This includes an **outlet stack** high enough for the safe discharge of the gases.
- **Silencer** in the outlet stack reduces the noise to acceptable levels.
- In Combined Cycle power plants the exhaust system has a 'diverter damper' to change the flow of gases to the Heat Recovery Boilers instead of the outlet stack.

3-Starting System

- Starting system provides the **initial momentum** for the Gas Turbine to reach the operating speed. This is similar to the starter motor of your car. The gas turbine in a power plant runs at 3000 RPM (for the 50 Hz grid - 3600 RPM for the 60 Hz grid). During starting the speed has to reach at least 60 % for the turbine to work on its own inertia. The simple method is to have a **starter motor with a torque converter** to bring the heavy mass of the turbine to the required speed. For large turbines this means a big capacity motor. **The latest trend is to use the generator itself as the starter motor with suitable electronics.** In situations where there is no other start up power available, like a ship or an off-shore platform or a remote location, **a small diesel or gas engine is used.**

4-Fuel System

- The Fuel system prepares a **clean fuel** for burning in the combustor. Gas Turbines normally burn **Natural gas** but can also fire diesel or distillate fuels. Many Gas Turbines have dual firing capabilities.
- A **burner** system and **ignition** system with the necessary safety interlocks are the most important items. A **control valve** regulates the amount of fuel burned . A **filter** prevents entry of any particles that may clog the burners. Natural gas directly from the wells is scrubbed and cleaned prior to admission into the turbine. **External heaters** heat the gas for better combustion.
- For liquid fuels **high pressure pumps** pump fuel to the pressure required for fine atomization of the fuel for burning



III - ISO rating of Gas Turbines

- The same Gas Turbine performs differently in the **high altitudes** of LaPaz, Bolivia and the **tropical island** of Singapore. It performs differently in **winter** and in **summer** in the Saudi Arabian deserts. **This has to do nothing with the Gas Turbine itself, but is due to the ambient atmospheric conditions.**
- For example : The manufacturers brochure promises a machine capable of 100 MW output at an efficiency of 35 %. But the actual performance is different. This is not due to the fault of the machine, but because of the different ambient conditions.
- To eliminate such misunderstandings, the gas turbine output and performance is specified at Standard conditions called the ISO ratings. These are specified as per ISO standards 3977-2 (Gas Turbines - Procurement - Part 2: Standard Reference Conditions and Ratings).
- The Standard conditions are explained below.

1-Ambient temperature, Relative Humidity, and Elevation.

- The three standard conditions specified in the ratings are Ambient Temperature - 15 deg C, Relative Humidity - 60 % and Ambient Pressure at Sea Level.
- These conditions affect the air density. How does air density affect the Gas Turbine output and performance ?
- The compressor section in a fixed volume of air for each rotation of the blades. The mass of the air depends on the air density. So at sea levels one rotation sucks in more kg of air than at place at high altitude.
- The work done by the gas turbine i.e.: the heat energy to mechanical [energy](#) conversion depends on the mass of the hot gases, the specific heat and the Temperature difference.
- The mass of the hot gases depend on the mass of the air that is taken in. This means at sea level the Gas turbine gives more output than at high altitudes.

2-Inlet and Exhaust Losses.

- The standard conditions specify that Inlet and Exhaust losses as Zero.
- The intake system and the exhaust system offer resistance to the flow of air and the exhaust gases. The energy to overcome these resistances comes from the Gas Turbine. This reduces the nett output of the Gas Turbine. The configuration and layout of the intake and exhaust systems varies from plant to plant and accordingly the losses. These losses reduce the actual output of the Gas Turbine from the rated value.

3-Base Load Operation at 100 % rated power.

- The standard considers that the Gas Turbine operates at 100 % rated load. The efficiency quoted at the standard ratings are for this 100 % Load. Efficiency of the gas turbine at part load operations is different from that at 100 % load. If you buy a machine rated at 100 MW and operate it at 75 MW you will not get the rated efficiency.
- The performance of a plant operating as a base load plant is different than a peaking load plant. This is mainly due to the frequent starts and stops that lead to deterioration of the performance.

4-Corrections.

- All the manufacturers provide correction factors for deviations from the various standard ratings discussed above. If the actual conditions are known the output and efficiency at the standard ratings is corrected to the actual conditions. Consider these corrections when specifying, purchasing and operating Gas Turbine power plants.
- Understanding of the ISO ratings and the actual plant conditions is essential when specifying and buying a Gas Turbine. Also this can be used to compare the performance of Gas Turbines.

Chapter Three

GAS TURBINE POWER PLANT

3.3 - THEORETICAL ANALYSIS

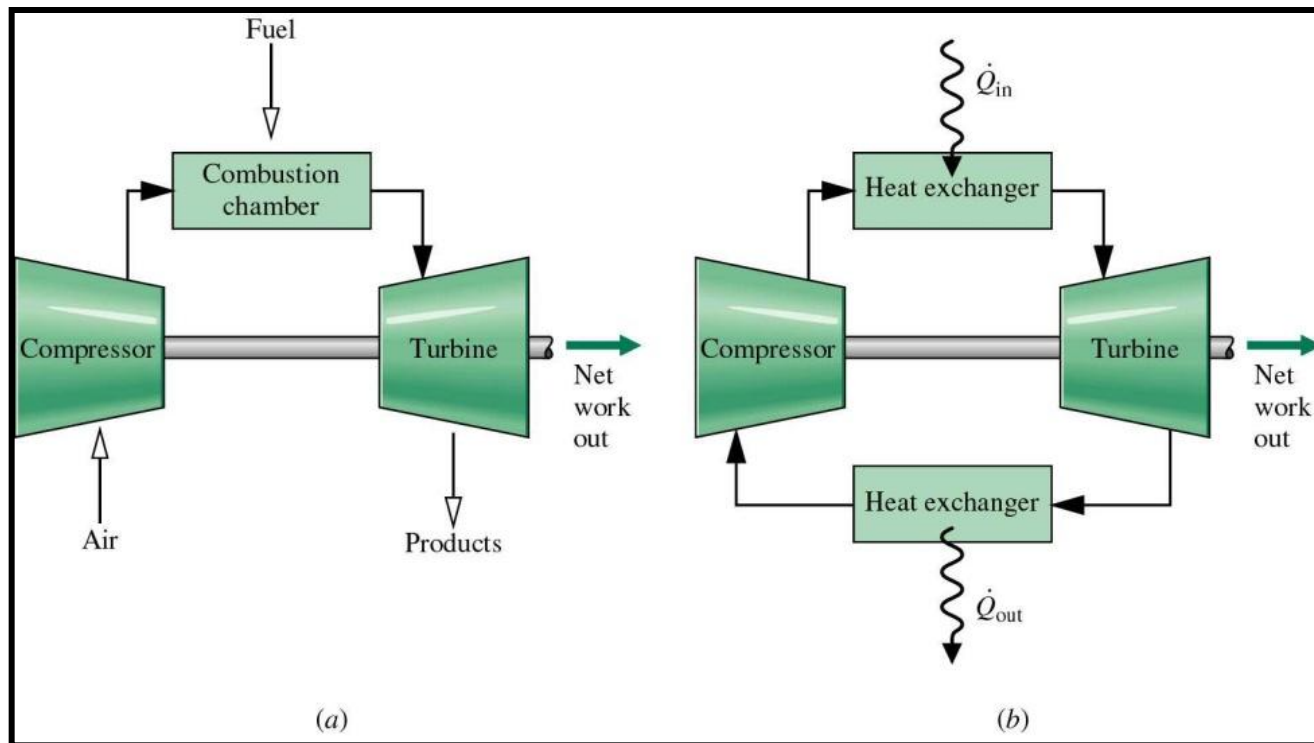
Brayton cycle

The ideal cycle for gas turbine is **Brayton** cycle (also known as **Joule** cycle). This ideal cycle is a **closed type**, using perfect gas as working fluid, where **specific heat** is assumed **constant**.

The simplified schematic of the Brayton cycle can be seen in this fig.

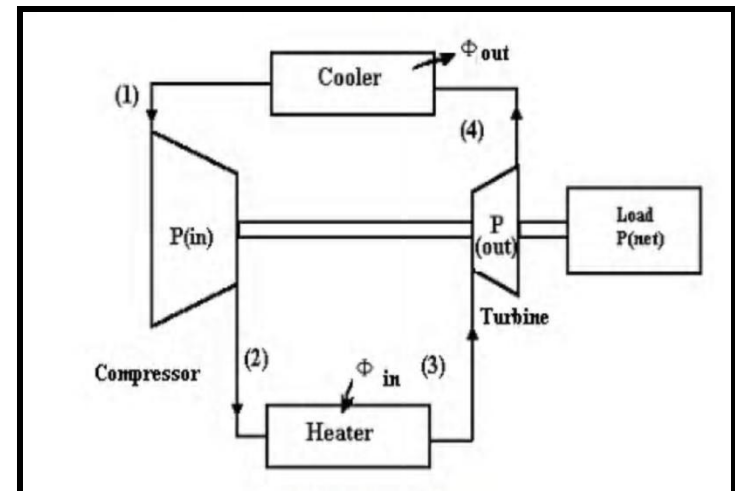
(a). the open cycle.

(b) Brayton cycle as a closed system.



The Brayton Cycle works as follows:

1. Ambient air is drawn into the compressor and brought to a higher pressure, also increasing its temperature. This requires work input, (W_{in}). Because it is a work required, we want this value to be as small as possible
2. The high pressure air then proceeds to the combustion chamber, where our fuel is mixed with the air and combusted. This is modeled as a constant pressure heat addition (Q_{in}).
3. The resulting high temperature gasses enter the turbine, where they are expanded to a lower pressure. The turbine extracts work from the fluid (W_{out}), producing a torque on the shaft that is connected to the compressor. The work created by the turbine needs to be only large enough to drive the compressor and auxiliary components.
4. Finally, when modeling this as a closed cycle, the exhaust gasses can be modeled as a constant pressure heat rejection.



Referring to the schematic , $T-s$, and PV diagrams below (fig.4), the theoretical analysis of this cycle will be based on the following assumptions :

- i – working fluid is air
- ii – heat supplied and heat rejected occur reversibly at constant pressure.
- iii – expansion and compression processes are isentropic

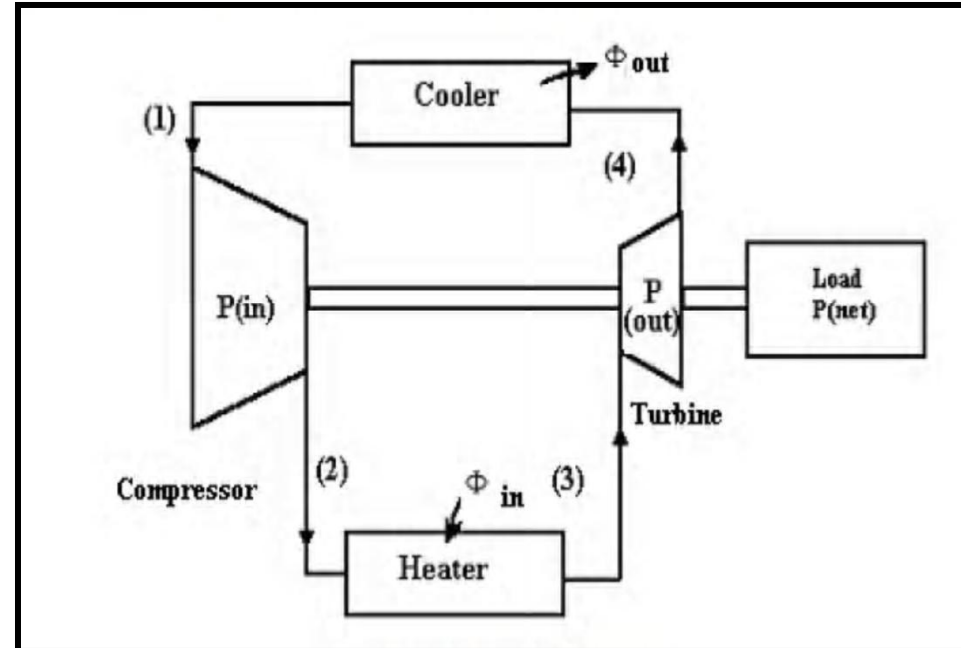
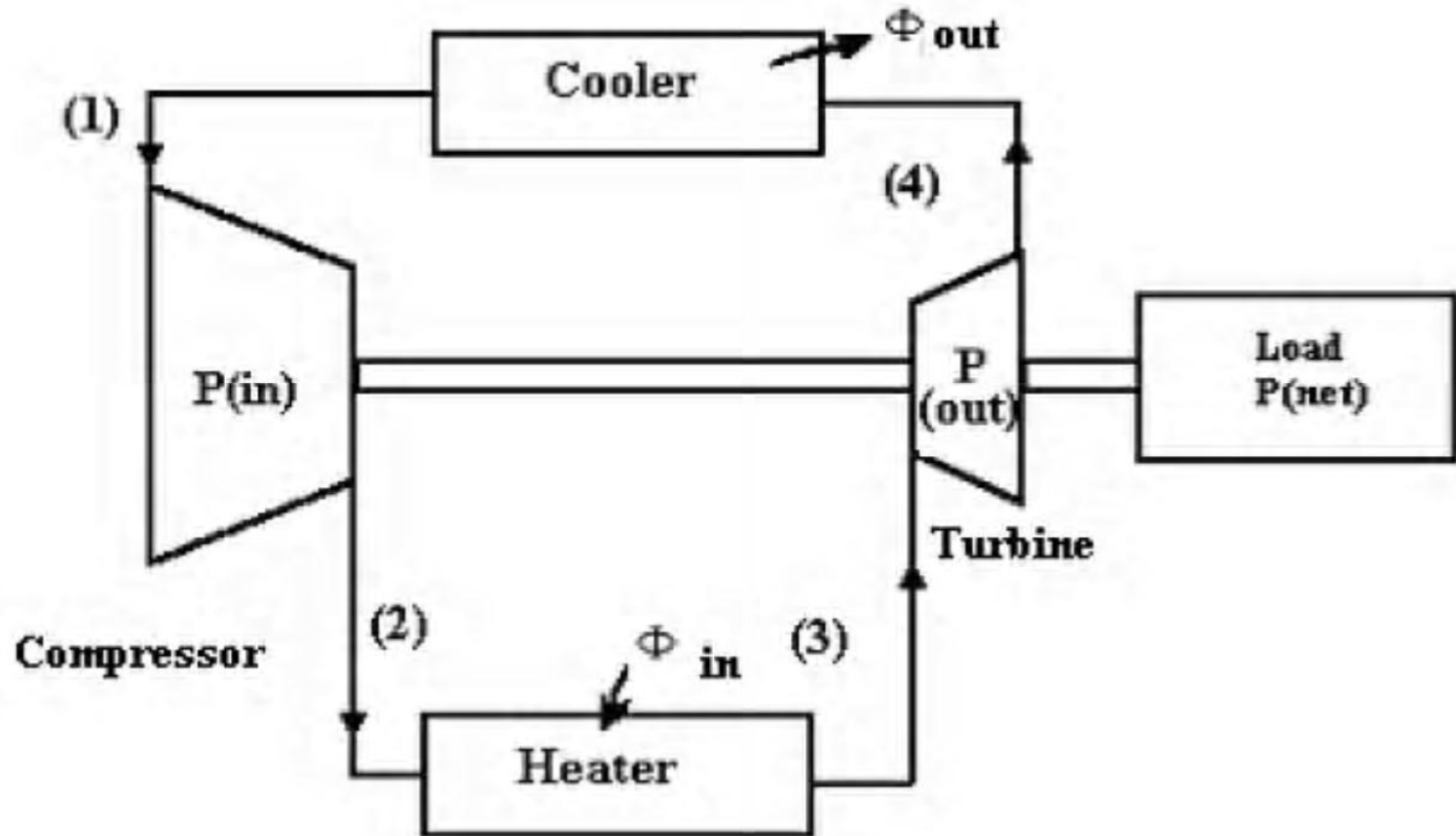


Fig. 4 - schematic



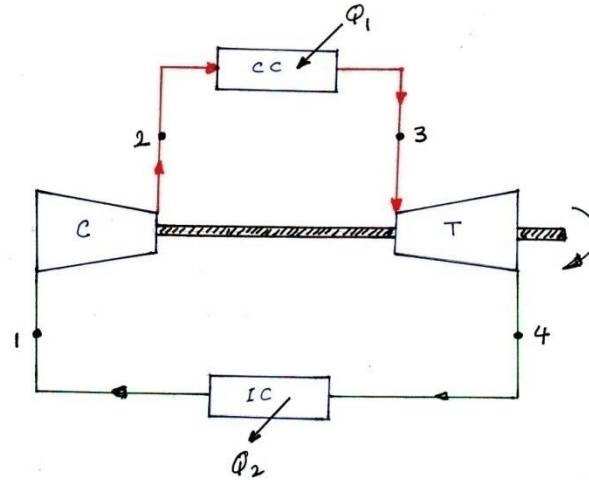
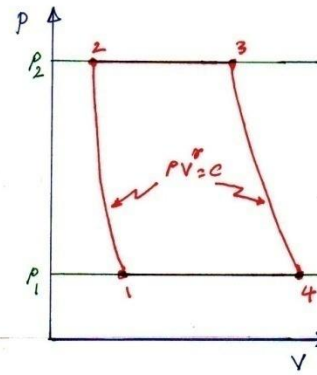
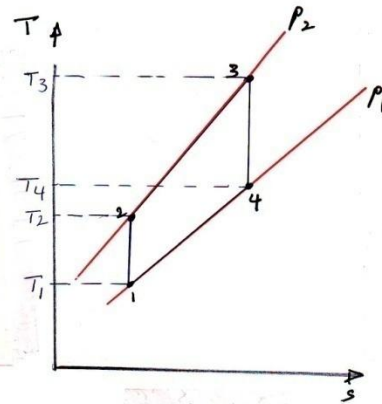


Fig-4

Work input to compressor

$$\text{eq.1 // } h_2 - h_1 = C_p (T_2 - T_1)$$

Work output from turbine

$$\text{eq.2 // } h_3 - h_4 = C_p (T_3 - T_4)$$

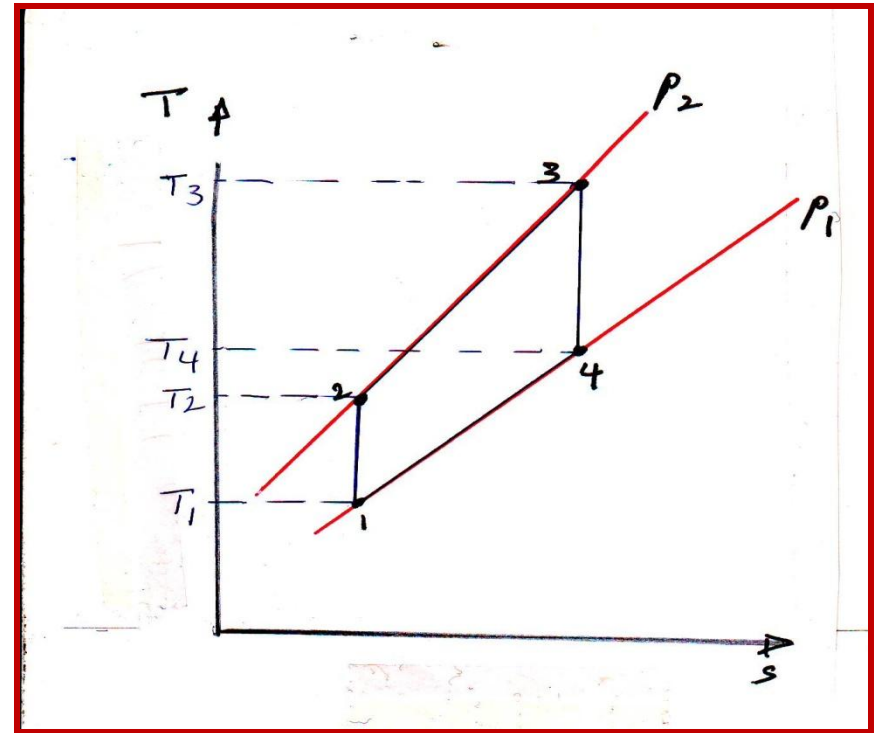
Heat supplied in heater

$$\text{eq.3 // } h_3 - h_2 = C_p (T_3 - T_2)$$

Heat rejected in cooler

$$\text{eq.4 // } h_4 - h_1 = C_p (T_4 - T_1)$$

Where processes : $1 \rightarrow 2$ and $3 \rightarrow 4$
are isentropic



The Brayton cycle governs the behavior of the gas turbine, where (fig.4) illustrates an ideal Brayton cycle, where it has

two adiabatic-reversible (isentropic) and
two constant pressure (isobaric) processes.

4.1 - Derivation of Thermal Efficiency

- $\eta = 1 - \frac{Q_2}{Q_1}$ eq.5

-

- $\eta = 1 - \frac{C_p(T_4 - T_1)}{C_p(T_3 - T_2)}$

$$\eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \quad \text{eq.6}$$

$$\text{let } \frac{p_2}{p_1} = r_p \quad \text{pressure ratio}$$

$$\text{and } \frac{\gamma - 1}{\gamma} = n$$

For isentropic process

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^n = \frac{T_3}{T_4} = r_p^n$$

$$T_2 = T_1 \cdot r_p^n$$

$$T_3 = T_4 \cdot r_p^n$$

$$(T_3 - T_2) = r_p^n \cdot (T_4 - T_1)$$

Since for thermal efficiency

$$\eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

Sub. For T_3 & T_2

$$\eta = 1 - \frac{(T_4 - T_1)}{r_p^n \cdot (T_4 - T_1)}$$

$$\eta = 1 - \frac{1}{r_p^n}$$

$$\eta = f(r_p)$$

Ideally for air ($\gamma=1.4$), but in practice, losses in compressor and turbine reduces the thermal efficiency compared to that evaluated in the above equation

4.2 - Work Ratio

Work ratio = net work / gross work

Net work : is the work available at shaft output after its reduction due to compressor & auxiliaries consumption

Gross work : is the work produced by the turbine

$$\begin{aligned}\text{NW} &= \text{work produced by turbine} - \text{work consumed by compressor} \\ &= C_p (T_3 - T_4) - C_p (T_2 - T_1)\end{aligned}$$

$$\begin{aligned}\text{NW} &= C_p [(T_3 - T_4) - (T_2 - T_1)] \\ \text{GW} &= C_p (T_3 - T_4)\end{aligned}$$

Therefore

$$\begin{aligned}\text{WR} &= \text{NW} / \text{GW} = C_p [(T_3 - T_4) - (T_2 - T_1)] / C_p (T_3 - T_4) \\ \text{WR} &= 1 - (T_2 - T_1) / (T_3 - T_4)\end{aligned}$$

But $(T_2 = T_1 \cdot r_p^n)$ and $(T_4 = T_3 / r_p^n)$

Therefore, sub in WR equation to obtain

$$\text{WR} = 1 - [(T_1(r_p^n - 1)) / (T_3(1 - (1/r_p^n)))]$$

Rearranging and simplifying

$$\text{WR} = 1 - [(T_1 / T_3) r_p^n]$$

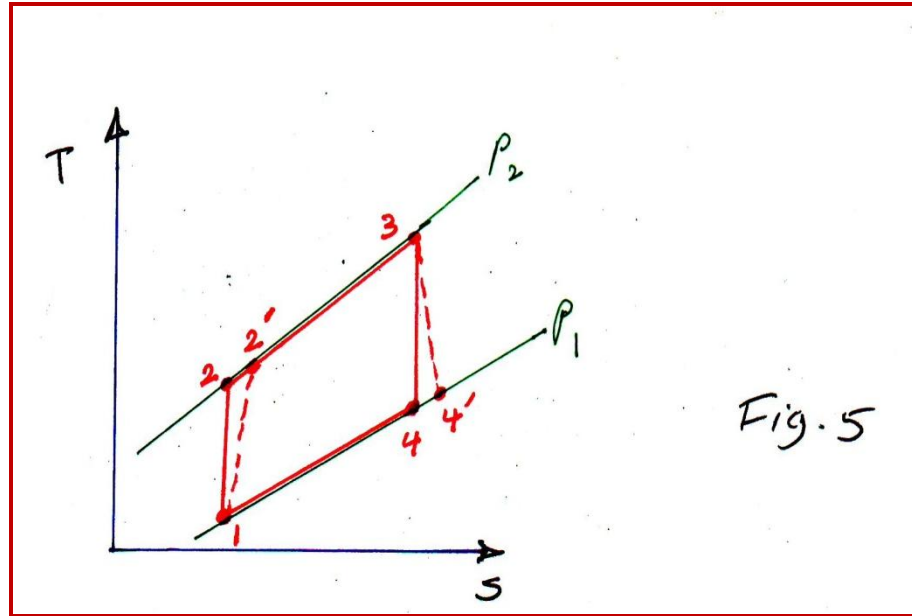
- since T_1 = minimum temperature
- T_3 = maximum temperature
- and so ,
- $WR = f (r_p , (T_{\min} / T_{\max}))$
- From this function, for a given inlet temperature (T_1),
- the max temp (T_3) must be raised as high as possible to have high (WR).

4.3 - Actual and Isentropic operating conditions

The open cycle (which is assumed actual cycle), cannot be compared directly with the ideal constant pressure cycle. The actual cycle involves the followings :

- 1- chemical reaction takes place in the combustion chamber which results in :
 - a- high temperature
 - b- combustion products chemically different from the reactants.
 - c- no energy exchange with the surroundings
- 2 – gradual decrease in chemical energy with the corresponding increase in enthalpy of the working fluid.
- 3 – chemical energy released from combustion process is equivalent to constant pressure heat transfer to the working fluid.
- 4 – working fluid assumed to have constant specific heat, as actual (C_p) varies with temperature.
- 5 – pressure loss in the combustion chamber is assumed negligible.

Remarks (3-5) are based on assumptions to allow ideal and actual cycle to be drawn on T - s diagram as shown in (fig.5) below, from which the followings are concluded :

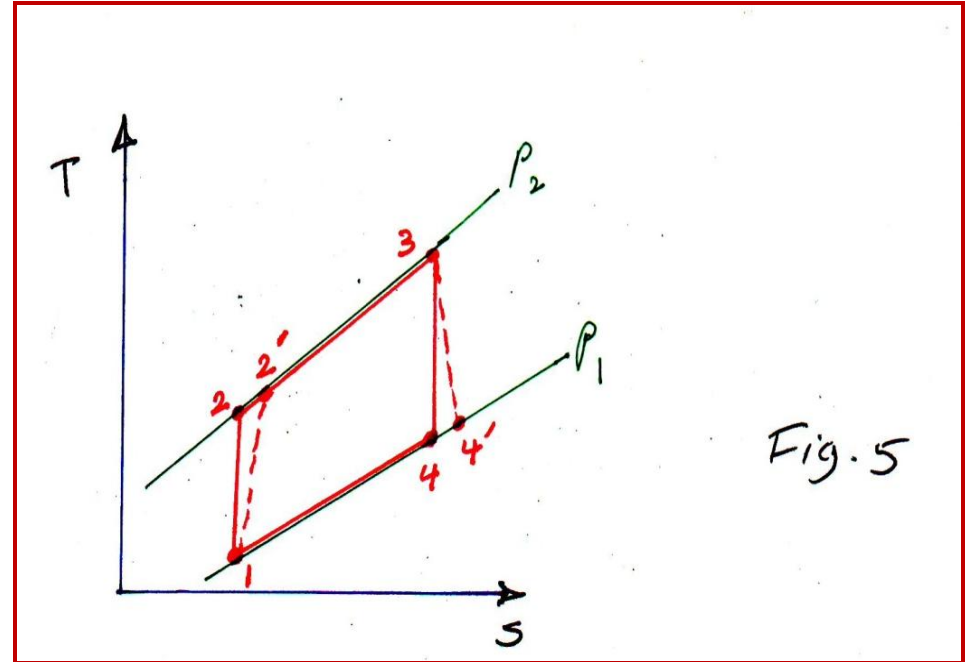


- 1 - 2' : irreversible adiabatic compression
- 2' - 3 : constant pressure heat supplied
- 3 - 4' : irreversible adiabatic expansion
- 1 - 2 : ideal isentropic compression
- 3 - 4 : ideal isentropic expansion

Actual and isentropic processes both occurs between same pressures (P_1, P_2)
Therefore

- i – compressor work input
= $C_p (T_2^- - T_1)$
- ii – combustion chamber heat addition
= $C_p (T_3 - T_2^-)$
- iii – turbine work output
= $C_p (T_3 - T_4^-)$

$$- T_1) - C_p (T_2^- - T_1) = C_p (T_3 - T_4^-)$$



and

$$\text{thermal efficiency} = \frac{\text{net work}}{\text{heat supplied}}$$

$$\eta_{th} = \frac{C_p (T_3 - T_4^-) - C_p (T_2^- - T_1)}{C_p (T_3 - T_2^-)}$$

Approximation are made in the above analysis as follows :

- i – although (C_p) varies with (T), and (C_p) for gases in combustion and turbine differ from that in compressor , mean value of (C_p) is assumed to simplify calculation.
- ii – mass rate in compressor is less than that in combustion chamber and turbine, as only air flows through compressor, while a mixture of (air + fuel) flows in combustion chamber and turbine .

4.4 – Compressor & Turbine Isentropic Efficiency

The isentropic efficiency of compressor is the ratio of the work input required in isentropic compression between (P_1 & P_2) to the actual work required, i.e

$$\eta_{ic} = \frac{C_p (T_2 - T_1)}{C_p (T_2^- - T_1)}$$

$$\eta_{ic} = \frac{(T_2 - T_1)}{(T_2^- - T_1)}$$

Similarly for turbine

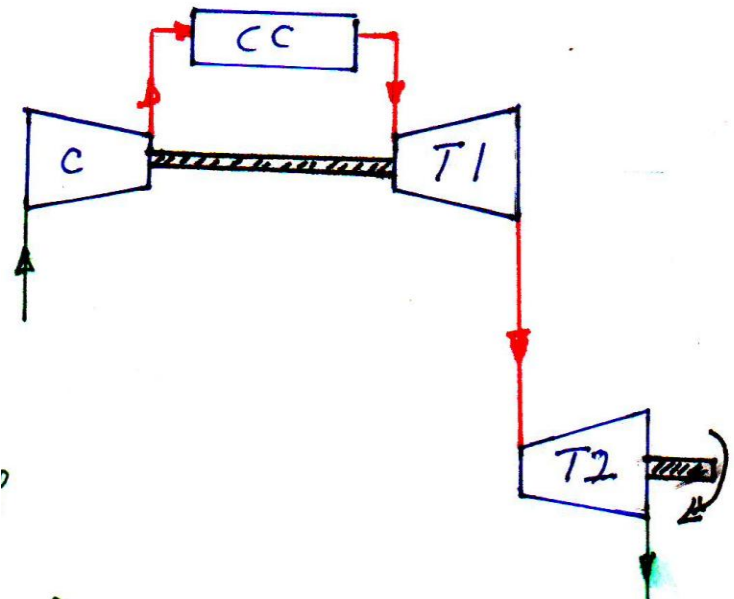
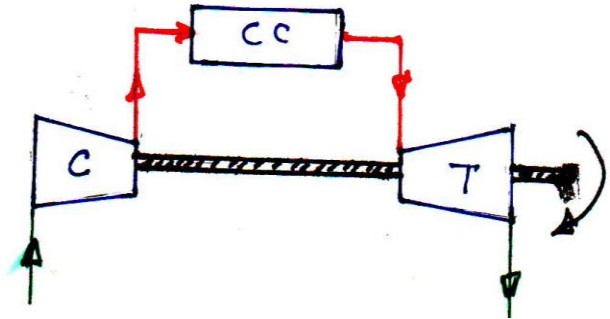
$$\eta_{it} = \frac{C_p (T_3 - T_4^-)}{C_p (T_3 - T_4)}$$

Therefore

$$\eta_{it} = \frac{(T_3 - T_4^-)}{(T_3 - T_4)}$$

In general, the work output from the turbine is used to drive the compressor, and also to supply the necessary work to drive the electrical generator.

However, it is quite common that two separate turbines are incorporated in the system, one to drive the compressor and the other to drive the generator.



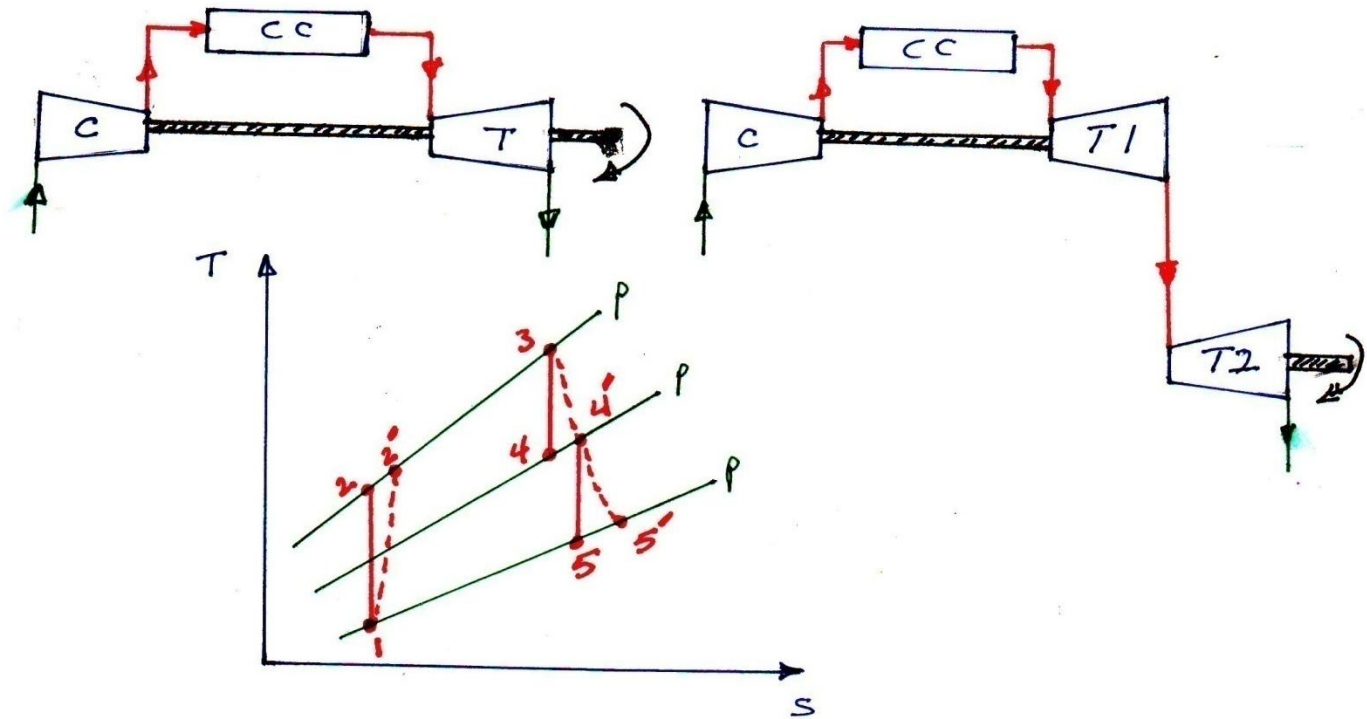


Fig - 6

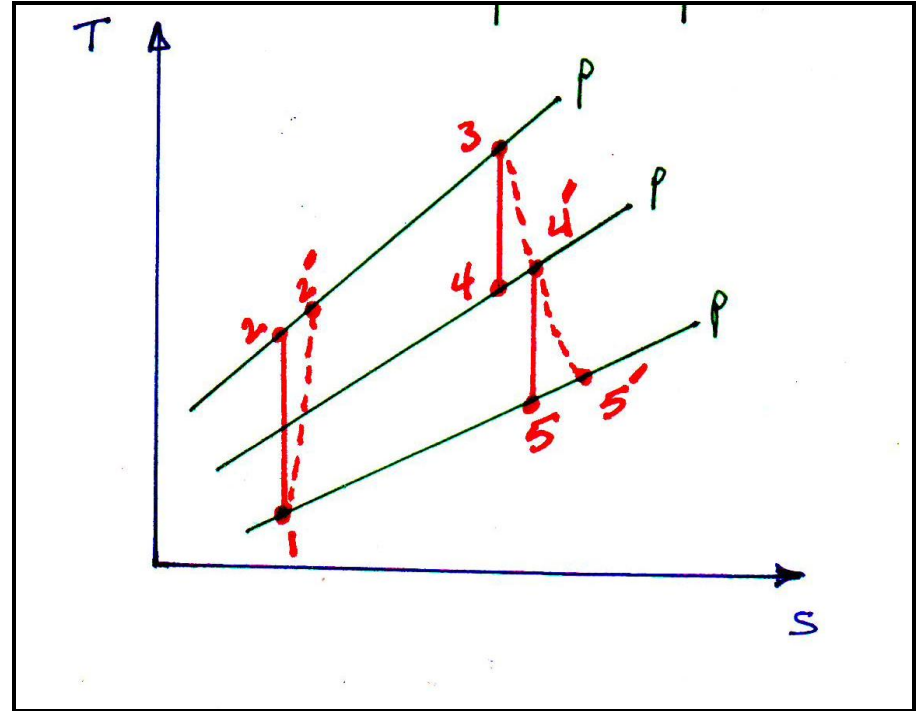
Where, see (fig. 6) for notation used

i – the first turbine (T1) is a HP turbine used to drive the compressor, this is also known as “compressor turbine”, and the work output from this HP turbine is the work input to the compressor, i.e

$$C_{pg} (T_3 - T_4^-) = C_{pa} (T_2^- - T_1)$$

C_{pg} : specific heat of gases in turbine

C_{pa} : specific heat of air in compressor



ii – the second turbine (T2) is a LP turbine used to drive the generator, which is also known as “power turbine”, and the work output from the LP turbine is the net work output to drive the generator, and is expressed as follows :

$$\text{net work output} = C_{pg} (T_4^- - T_5^-)$$

Chapter Three

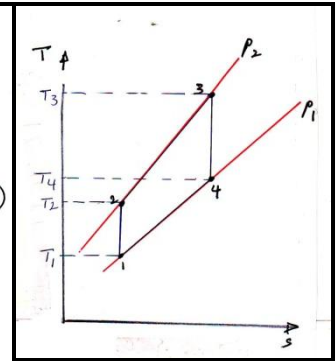
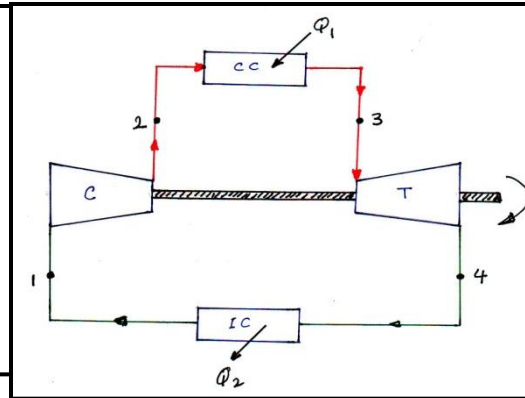
GAS TURBINE POWER PLANT

3.4 - Regeneration

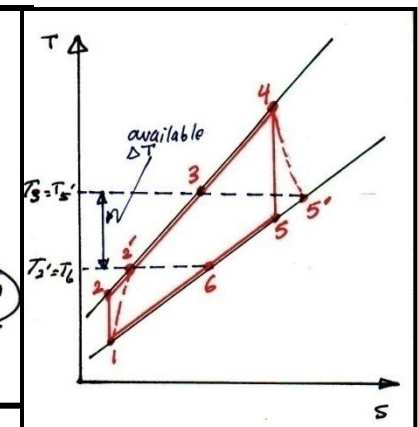
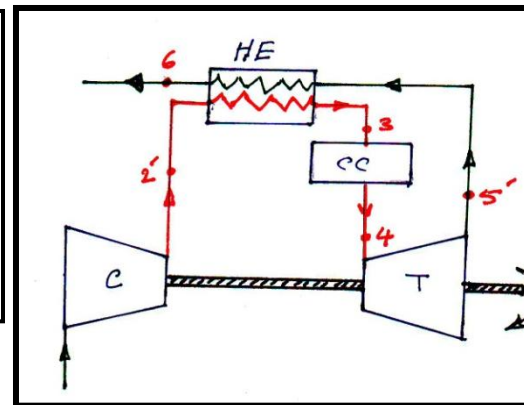
As shown previously that the temperature of gases exhausted from turbine is higher than that of air after compressor, i.e

$$T_4 > T_2$$

This means that heat energy is wasted, unless utilized by some means.



This would be done by applying heat exchanger to transfer heat from exhaust gases to the compressed air located before combustion chamber, as shown in this figure



schematic diagram

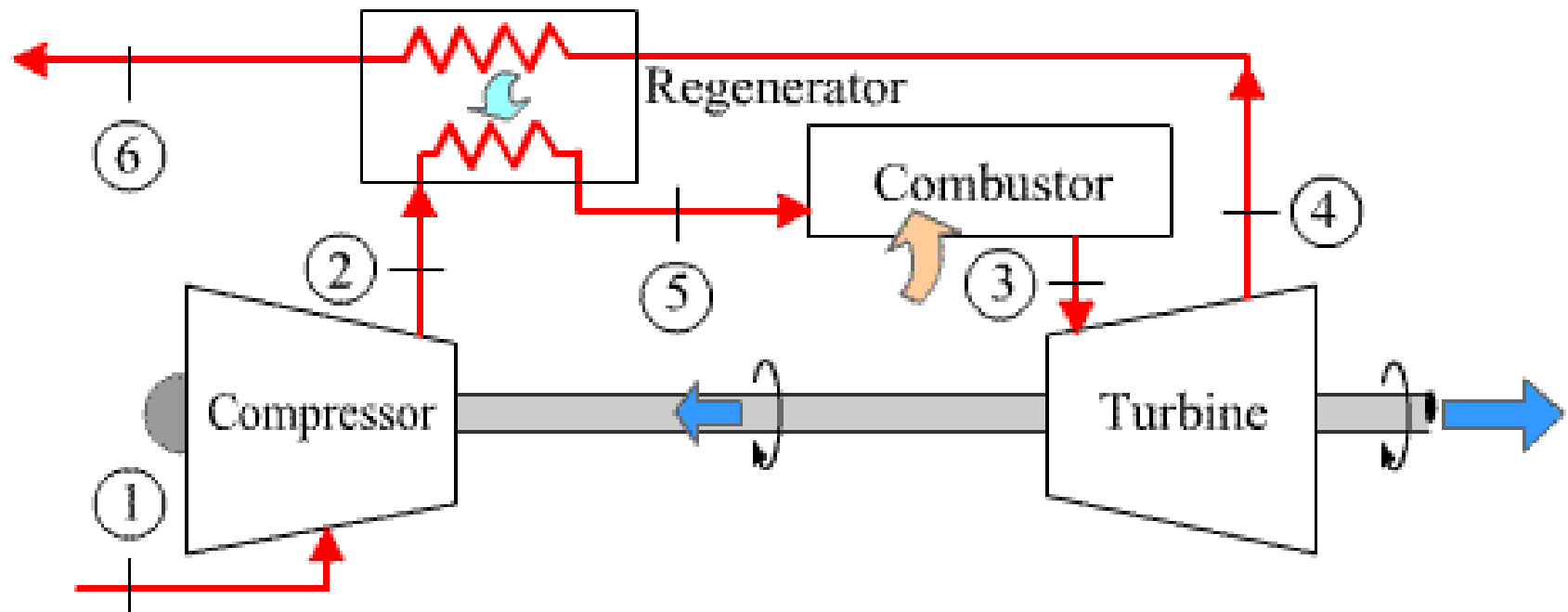
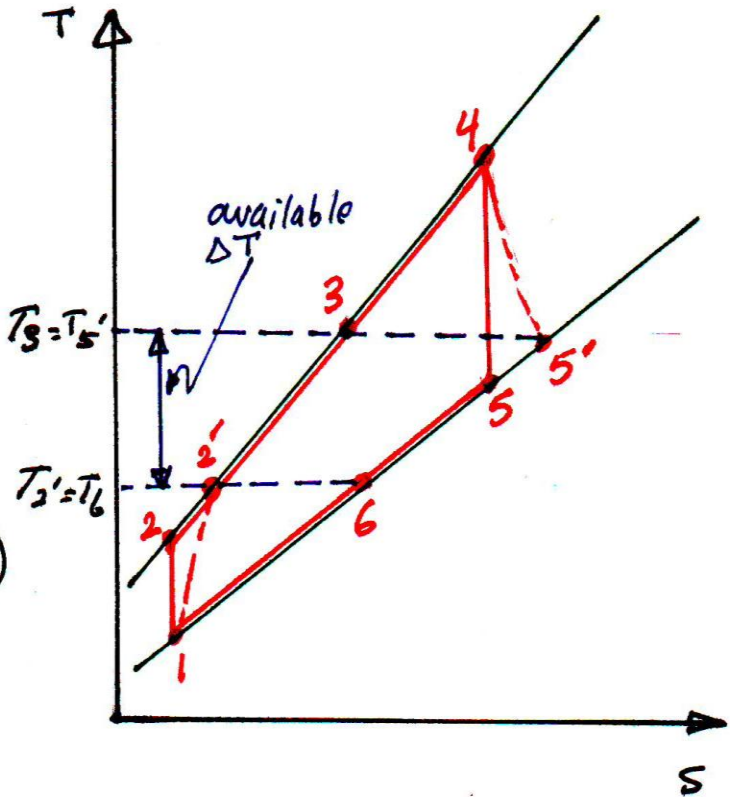
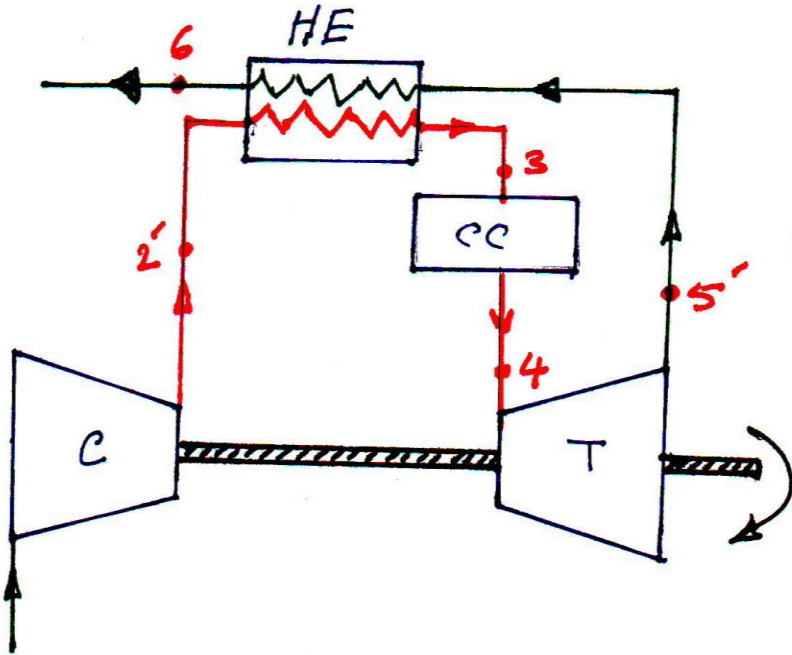


Fig. 7



Ideally

Air is heated from T_2^- to T_3

Gases is cooled from T_5^- to T_6

Where ($T_3 = T_5^-$), and ($T_6 = T_2^-$)

This is an ideal case where no losses encountered in the heat exchanger, and so **all** the heat from exhaust gases are transferred to the compressed air.

In actual practice however, this is impossible, since (ΔT) must be available for the heat transfer to take place, i.e

T_6 must be $> T_2^-$

And

T_5^- must be $> T_3$

Then, the following ΔT must exist

$$\Delta T_i = T_6 - T_2^-$$

$$\Delta T_e = T_5^- - T_3$$

Also if no heat losses in the heat exchanger is assumed, then the heat energy lost from gases is equal to the heat energy gained by the air, i.e

$$m_g \cdot C_{pg} \cdot (T_5^- - T_6) = m_a \cdot C_{pa} \cdot (T_3 - T_2^-)$$

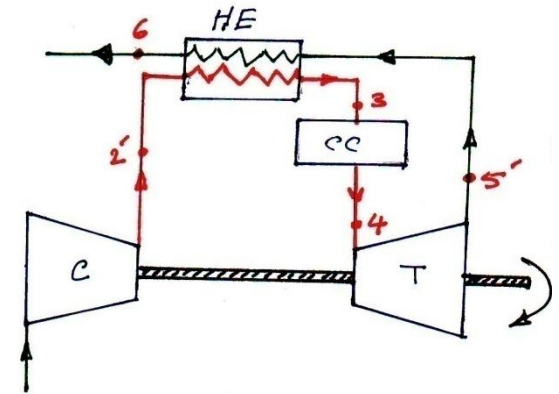
Maximum heat transfer in regenerator

1 – if

$(T_3 - T_2^-) = \text{rise in air temp.}$

Then heat energy gained by the air is

$$m_a \cdot C_{pa}(T_3 - T_2^-)$$

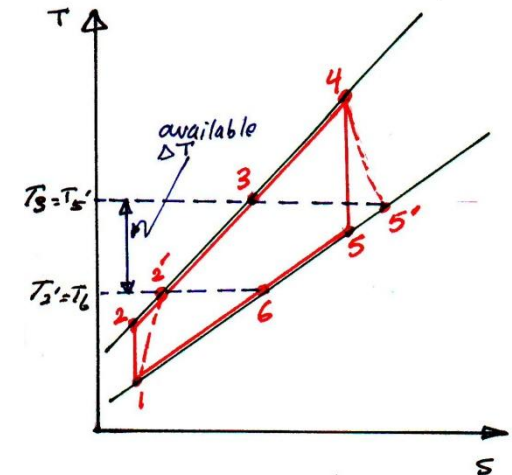


2 – and

$(T_5^- - T_2^-) = \text{max possible temp rise}$

Then max heat energy possible to be transferred from gases to air is

$$m_g \cdot C_{pg} (T_5^- - T_2^-)$$



Regenerator effectiveness

from these analysis the following terms are expressed :

i – heat exchanger effectiveness (ϵ)

A heat exchanger effectiveness is defined to allow for the temperature difference necessary for the transfer of heat between the turbine exhaust gas and the compressor outlet air i.e

heat received by the air

$$\text{Effectiveness} = \frac{\text{max possible heat which could be transferred from the gas in the heat exchanger}}{\text{heat received by the air}}$$

$$\epsilon = \frac{m_a \cdot C_{pa} (T_3 - T_2^-)}{m_g \cdot C_{pg} (T_5 - T_2^-)}$$

Normally
 $85\% \geq \epsilon \geq 70\%$

ii – heat exchanger thermal ratio (R_{th})

$$R_{th} = \frac{(T_3 - T_2^-)}{(T_5 - T_2^-)}$$

If [$m_a \cdot C_{pa} = m_g \cdot C_{pg}$],
then

$$\epsilon = R_{th}$$

Regenerative cycle efficiency

The simple cycle (η_{th}) is

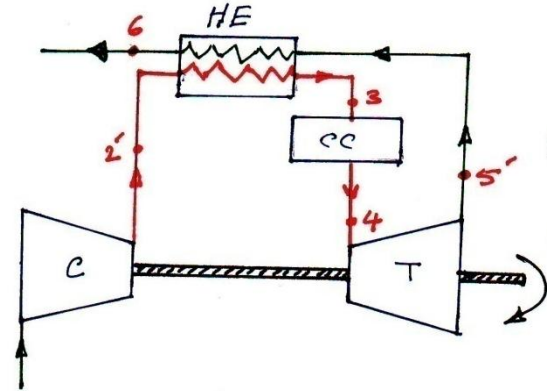
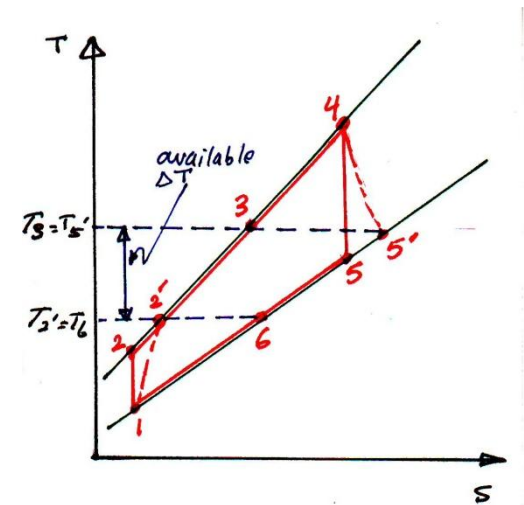
$$\eta_{th} = \frac{C_p (T_4 - T_5) - C_p (T_2 - T_1)}{C_p (T_4 - T_2)}$$

In this diagram for simple cycle with no regeneration, then state points (3 & 2') are actually coincides at same location that joins the compressor directly to the combustion chamber.

for ideal regenerative cycle [$T_3 = T_5$]
and so thermal efficiency will be expressed
as :

$$\eta_{th} = \frac{C_p (T_4 - T_5) - C_p (T_2 - T_1)}{C_p (T_4 - T_5)}$$

Rearranging to obtain $\rightarrow \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow$



$$\eta_{th} = 1 - \frac{(T_2 - T_1)}{(T_3 - T_4)}$$

Recalling equations for ideal cycle as below

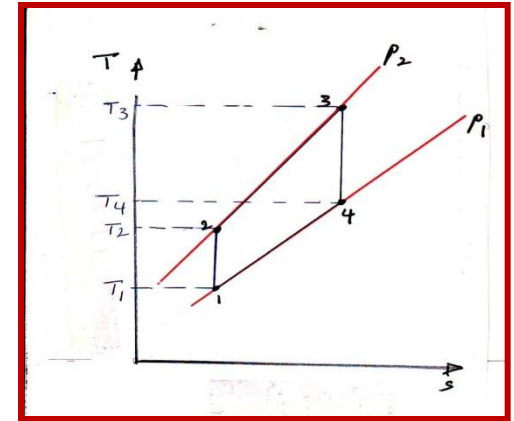
$$T_2 = T_1 \cdot r_p^n$$

$$T_3 = T_4 \cdot r_p^n$$

Where

$$T_3 = T_{\max}$$

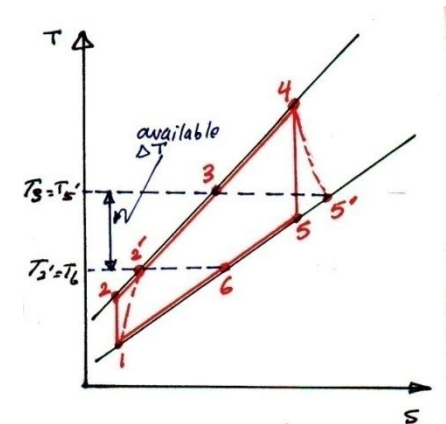
$$T_4 = T \text{ after turbine}$$



In regenerative cycle, notations differ, where max temp. is denoted by (4) and not (3), and similarly (5' instead of 4), i.e

$$T_4 = T_{\max}$$

$$T_{5'} = T \text{ after turbine}$$



$$T_2 = T_1 \cdot r_p^n$$

$$T_{5'} = T_4 / r_p^n$$

Sub in above

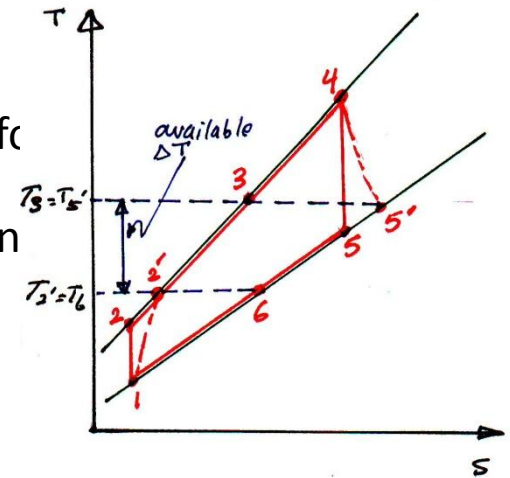
$$\eta_{th} = 1 - \frac{T_1 (r_p^n - 1)}{T_3 (1 - 1/r_p^n)}$$

→→→→

$$\eta_{th} = 1 - (T_1 / T_4) (r_p^n)$$

(see previous remarks)

Then the actual thermal efficiency under regeneration condition will be



$$\eta_{th,a} = \frac{C_p (T_4 - T_5) - C_p (T_2 - T_1)}{C_p (T_4 - T_3)}$$

Since

$$\eta_{th} = \frac{C_p (T_4 - T_5) - C_p (T_2 - T_1)}{C_p (T_4 - T_5)}$$

Therefore, under regenerative conditions

$$\eta_{\text{th.a}} < \eta_{\text{th}}$$

When a regenerator is used then the heat supplied in the (CC) combustion chamber is reduced for a given max cycle temperature due to the increase in air temperature entering (CC) by regeneration. The amount of heat added per kg of air is less than the simple cycle for all pressure ratios where the air temperature at the end of compression is lower than the gas temperature at the end of expansion, that is for

$$1 \leq r_p \leq (T_3/T_1)^{n/2}$$

Therefore, for the above range of pressure ratio, the efficiency of the cycle increases by regeneration.

$$\eta_{th} \text{ (regenerative)} > \eta_{th} \text{ (ideal)}$$

looking into the term $[(T_1/T_3) (r_p^n)]$
let

$$(r_p^n) = C$$

assuming that for such conditions this term remains constant
Therefore

for ideal cycle

$$\eta_{ideal} = 1 - 1/C$$

η_{th}

for regenerative cycle

$$\eta_{th} \text{ (regen)} = 1 - (T_1/T_3) C$$

it is obvious that $(T_1 < T_3)$

As T_1 is inlet to compressor

$$= T_{min} = T_{ambient}$$

T_3 is inlet to turbine

$$= T_{max}$$

Then

$$T_1/T_3 < 1$$

However, the work output in this regenerative cycle for unit mass flow .

$$W = C_p (T_4 - T_5^-) - C_p (T_2^- - T_1)$$

since

$$T_2^- = T_1 \cdot r_p^n$$

and

$$T_5^- = T_4 / r_p^n$$

Let $(r_p^n = Z)$ Sub is above

$$W = C_p (T_4 - T_5^-) - C_p (T_2^- - T_1)$$

$$W = C_p (T_4 - T_4 / Z) - C_p (T_1 \cdot Z - T_1)$$

$$W = C_p T_4 (1 - 1/Z) - C_p T_1 (Z - 1)$$

$$W = C_p T_1 \{ [(T_4 / T_1)(Z - 1) / (Z)] - (Z - 1) \}$$

$$W = C_p T_1 (Z - 1) \{ [(T_4 / T_1) / (Z)] - 1 \}$$

This means that

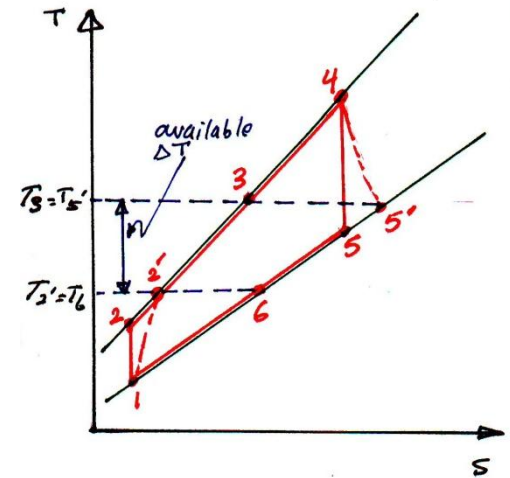
$$W = f(C_p, T_1, T_4, Z)$$

Since $(T_4 = T_{\max})$,

and for a given (working fluid, pressure ratio, and initial conditions),

then

$$W = f(T_{\max})$$



- From above it can be concluded for the regenerative cycle that
- Thermal efficiency is improved
- Work output remains the same
- This means that (better sfc for a given power output), and so, less fuel is consumed for the same power output

conclusions

- Regeneration can only be possible if there is a sufficient large temperature difference between the gases leaving the turbine (T_4) and the air leaving the compressor (T_2).
- If for some reasons (T_4) came out to be less than (T_2). Regeneration will be impossible in this case.
- If in the case that ($T_4 > T_2$) but (ΔT) between them may not be large enough to make the extra capital cost for adding regenerator a valid investment.
- Also if (ΔT) is small, then the surface area for the heat transfer must be made large in order to achieve a reasonable value of thermal ratio

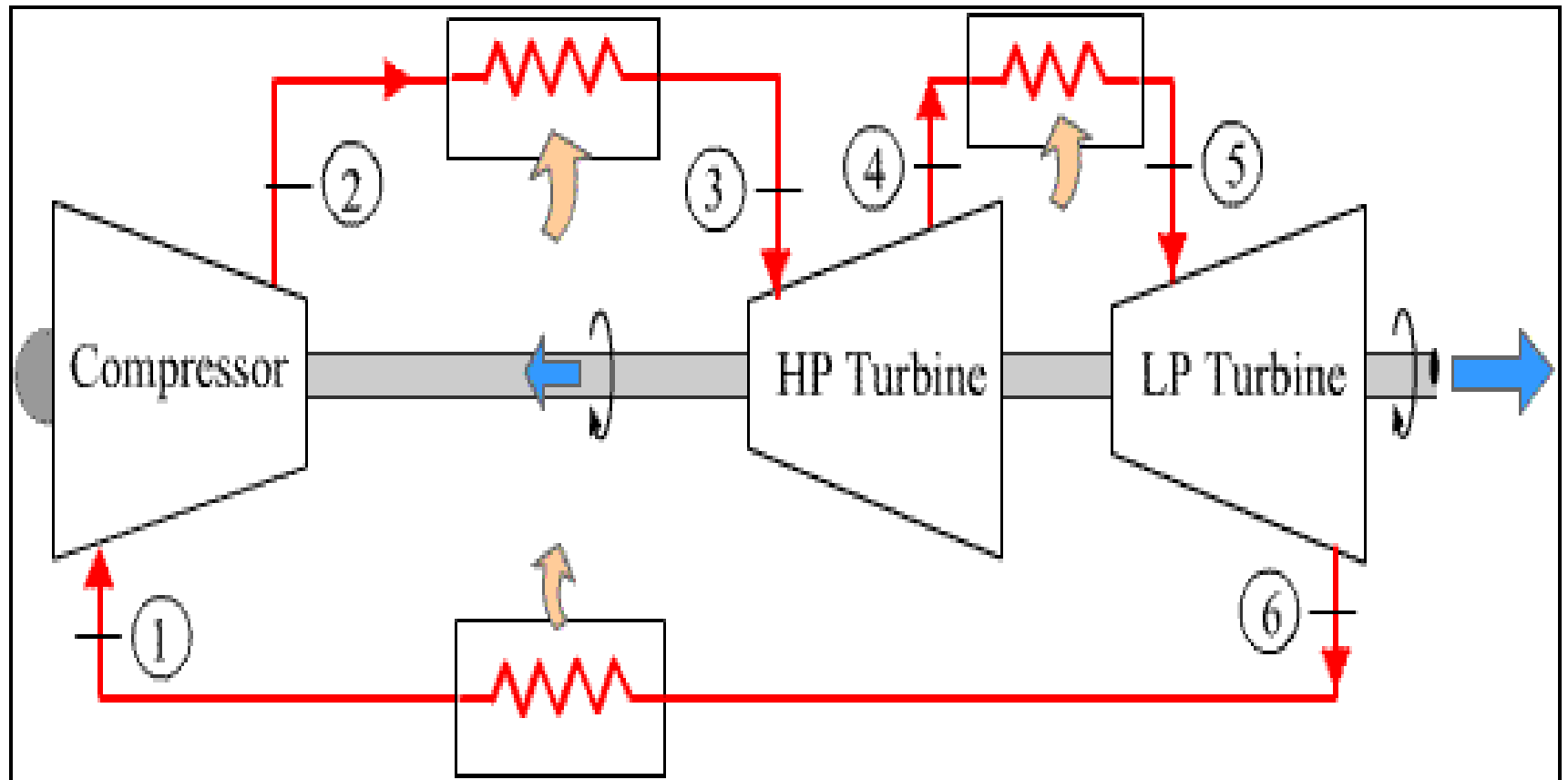
Chapter Three

GAS TURBINE POWER PLANT

3.5 - Reheating

What is reheating

- In reheating cycle, the the combustion gas expands into **two turbines** instead of one, where the exhaust of the first turbine (**HP**) is reheated in a reheater and then expands in the second turbine (**LP**).
- **By reheating,**
- the **power output** of the system is **increased**, but
- the **cost** of additional **fuel** consumption is also **increased**.



Brayton Cycle with Reheat

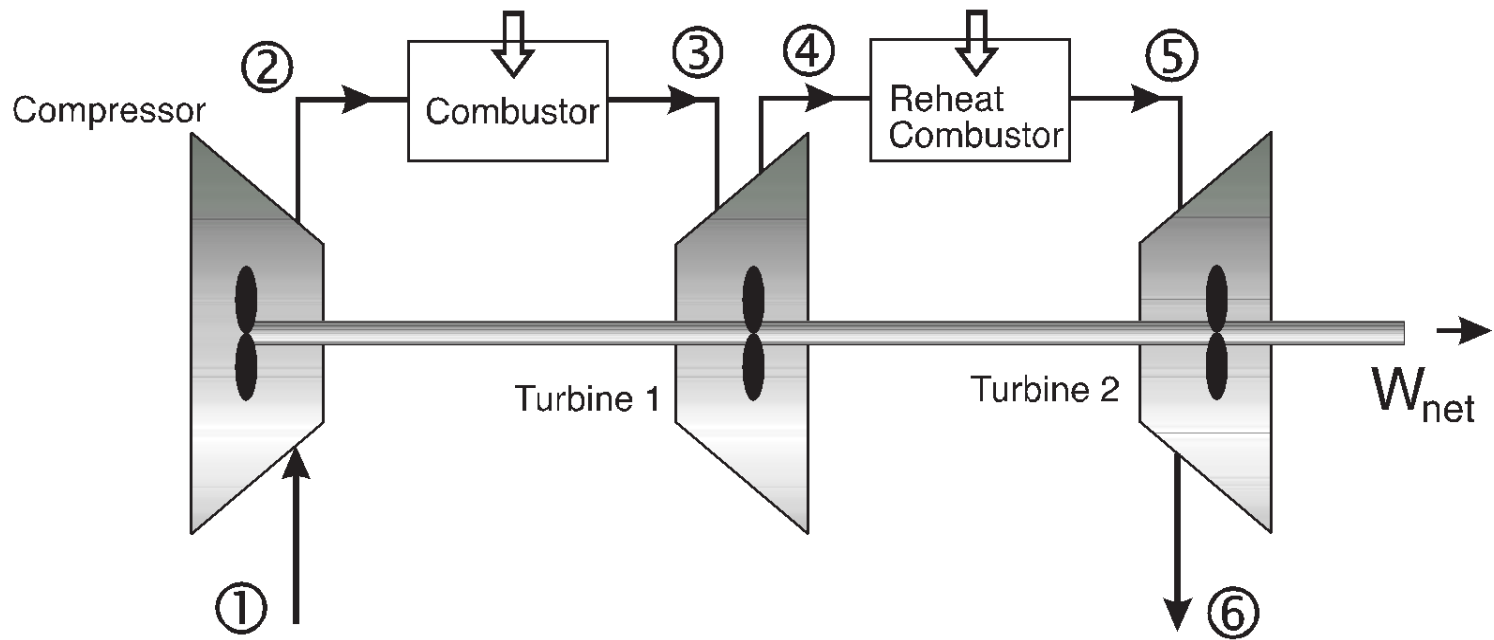
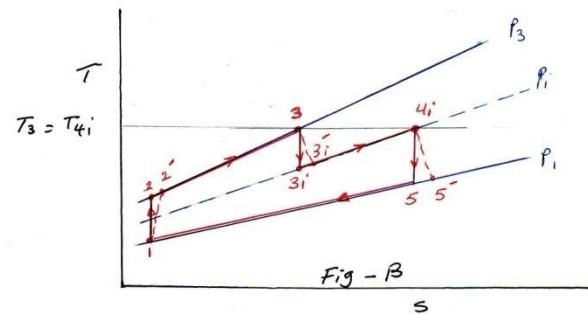
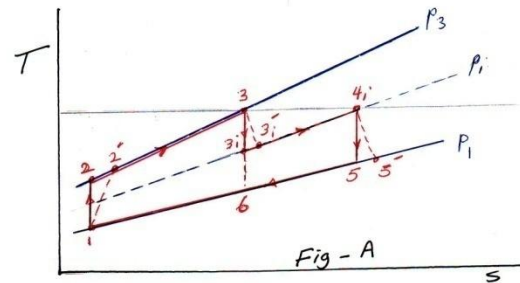
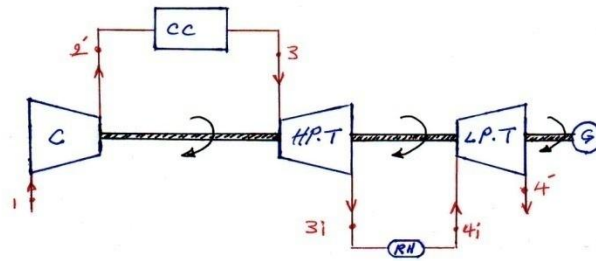


Fig.8



Ideal cycle

- In the ideal cycle
- $\text{Work output} = C_p (T_3 - T_{3i}) + C_p (T_{4i} - T_5)$
- If one turbine is used, then expansion will take place from (3) to (6), and the work output will accordingly be :
- $W = C_p (T_3 - T_6)$

Important remarks

Consider the value of the term
($T_3 - T_6$) as shown in fig.8A,
where

$$(T_3 - T_6) = (T_3 - T_{3i}) + (T_{3i} - T_6)$$

But is it true to conclude that
($T_3 - T_6$) = ($T_3 - T_{3i}$) + ($T_{4i} - T_5$)

Which means that
($T_{4i} - T_5$) = ($T_{3i} - T_6$)

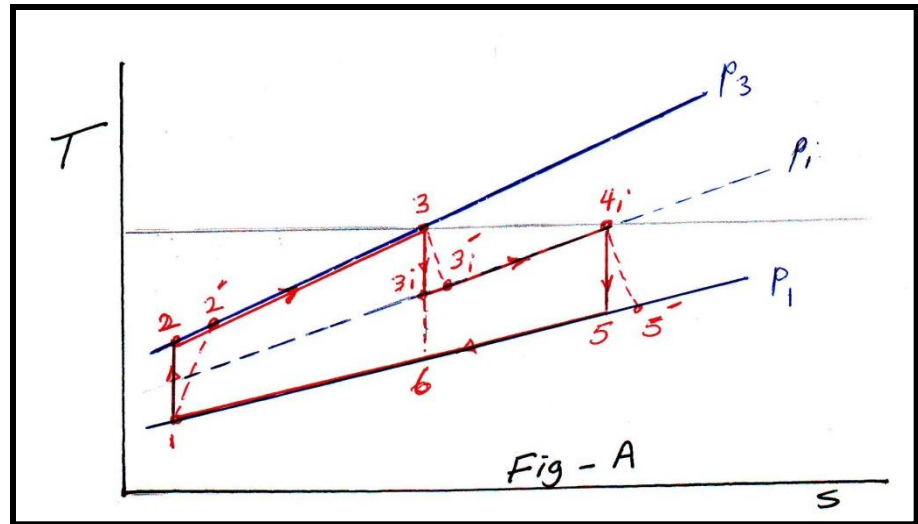
The answer is **NO**

Why ?

Because

$$(T_{4i} - T_5) \neq (T_{3i} - T_6)$$

Why ?



Because the constant pressure lines are not parallel, where they

Diverge away from origin

Converge in towards origin

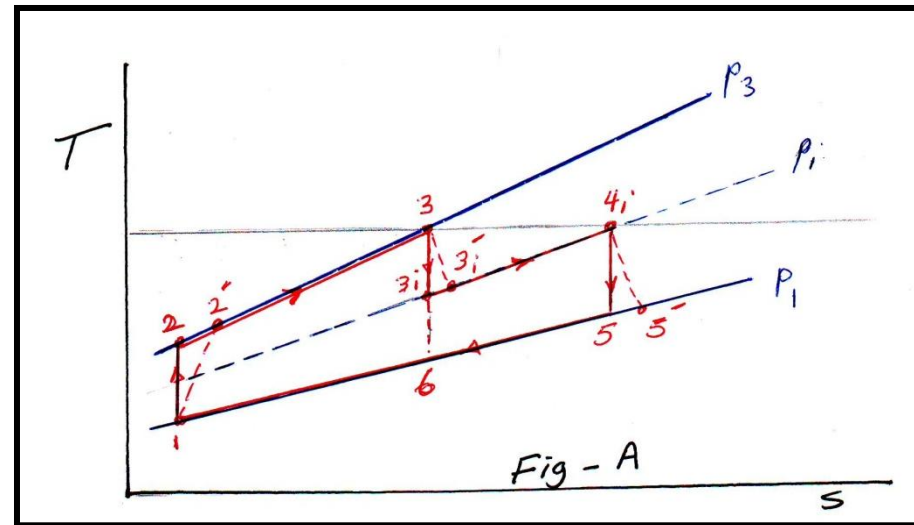
Therefore the magnitudes of the vertical line sectors

$$|4_i - 5| > |3_i - 6|$$

Which means that $(T_{4i} - T_5) > (T_{3i} - T_6)$

The difference results in power increase, and therefore we could finally conclude that

Reheating increases power output



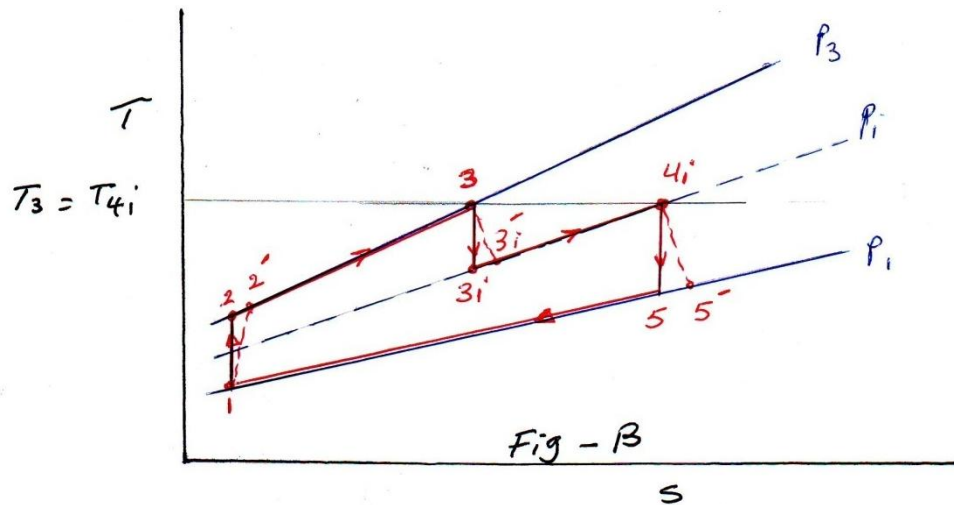
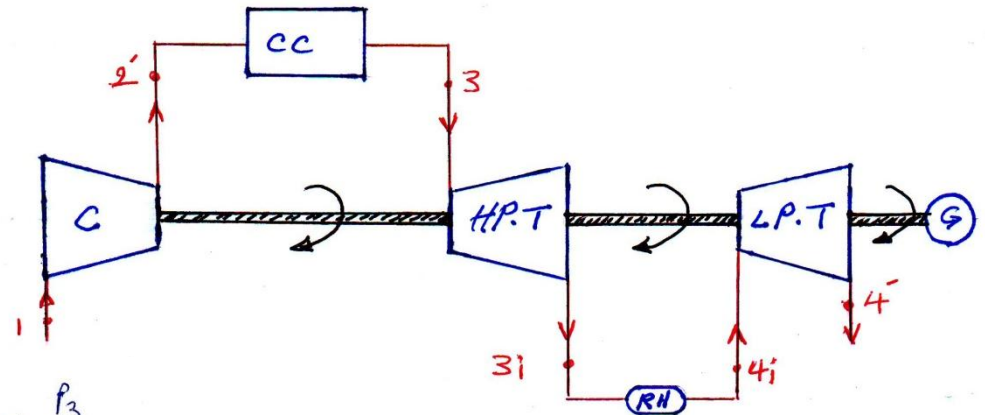
Work output

- And therefore, accordingly, the work output of the system under ideal considerations can be expressed as follows :
- **Work output = $C_p (T_3 - T_{3i}) + C_p (T_{4i} - T_5)$**

Thermal efficiency

Thermal efficiency for the ideal system can be expressed as follows, where the notation as shown in this fig.8B

$$\eta_{th} = \frac{c_p [(T_3 - T_{3i}) + (T_{4i} - T_5) - (T_2 - T_1)]}{c_p [(T_3 - T_2) + (T_{4i} - T_{3i})]}$$



Overall pressure ratio R_p

Assuming that reheating takes place in an intermediate pressure (P_i) between (P_3 and P_1), where

$$rp_1 = P_3 / P_i$$

And

$$rp_2 = P_i / P_1$$

And the overall pressure ratio is

$$rp = rp_1 \times rp_2$$

Let $n = (\gamma - 1) / \gamma$

then

$$rp^n = rp_1^n \times rp_2^n$$

or

$$1 / rp_2^n = (rp_1^n) / rp^n$$

η_{th} & W

- $$\eta_{th} = \frac{C_p [(T_3 - T_{3i}) + (T_{4i} - T_5) - (T_2 - T_1)]}{C_p [(T_3 - T_2) + (T_{4i} - T_{3i})]}$$

- **Work o/p = $C_p [(T_3 - T_{3i}) + (T_{4i} - T_5) - (T_2 - T_1)]$**

The gas is reheated back to the maximum temperature of the cycle , i.e

$$T_3 = T_{4i} = T_{\max}$$

$$W = C_p [T_3 - T_{3i} + T_{4i} - T_5 - T_{2^-} + T_1]$$

$$W = C_p [T_3 - T_{3i} + T_3 - T_5 - T_{2^-} + T_1]$$

$$W = C_p [2T_3 - T_{3i} - T_5 - T_{2^-} + T_1]$$

$$W = C_p T_1 [2T_3/T_1 - T_{3i}/T_1 - T_5/T_1 - T_{2^-}/T_1 + 1]$$

$$W = C_p T_1 [(2T_3/T_1) - (T_3/T_1 \cdot T_{3i}/T_3) - (T_{4i}/T_1 \cdot T_5/T_{4i}) - (T_{2^-}/T_1) + 1]$$

since

$$T_{3i}/T_3 = 1/r_{p1}^n$$

$$T_5/T_{4i} = 1/r_{p2}^n$$

$$T_{2^-}/T_1 = r_p^n$$

Where ($n = (\gamma - 1) / \gamma$)

Sub in above

$$W = C_p T_1 [(2T_3/T_1) - (T_3/T_1 \cdot 1/r_{p1}^n) - (T_3/T_1 \cdot 1/r_{p2}^n) - (r_p^n) + 1]$$

Therefore

$$W = f (T_1, T_3/T_1, r_{p1}^n, r_{p2}^n, r_p^n)$$

Max work output

As shown above, the work output is expressed as :

$$W = C_p T_1 \left[\left(\frac{2T_3}{T_1} \right) - \left(\frac{T_3}{T_1} \cdot \frac{1}{r_{p1}^n} \right) - \left(\frac{T_3}{T_1} \cdot \frac{1}{r_{p2}^n} \right) - (r_p^n) + 1 \right]$$

Differentiate with respect to (r_{p1}^n) and equate to zero

$$\frac{dw}{dr_{p1}^n} = C_p T_1 \left[\left(\frac{T_3}{T_1} \cdot \frac{1}{r_{p1}^{2n}} \right) - \left(\frac{T_3}{T_1} \cdot \frac{1}{r_p^n} \right) \right]$$

Since $C_p T_1 \neq 0$

And $(T_3/T_1) \neq 0$

Then

$$\left(\frac{1}{r_{p1}^{2n}} \right) - \left(\frac{1}{r_p^n} \right) = 0$$

From which both pressure ratios can be related as

$$r_{p1} = \sqrt{r_p}$$

For $(W_{\max}) \rightarrow \rightarrow r_p \text{ of HPT} = \sqrt{\text{total } r_p}$

Final conclusion

- In a reheating process
- I – power o/p increases
- II - η_{th} decreases due to high gas temperature at outlet of the last stage of the turbine (T_5)

Chapter Three

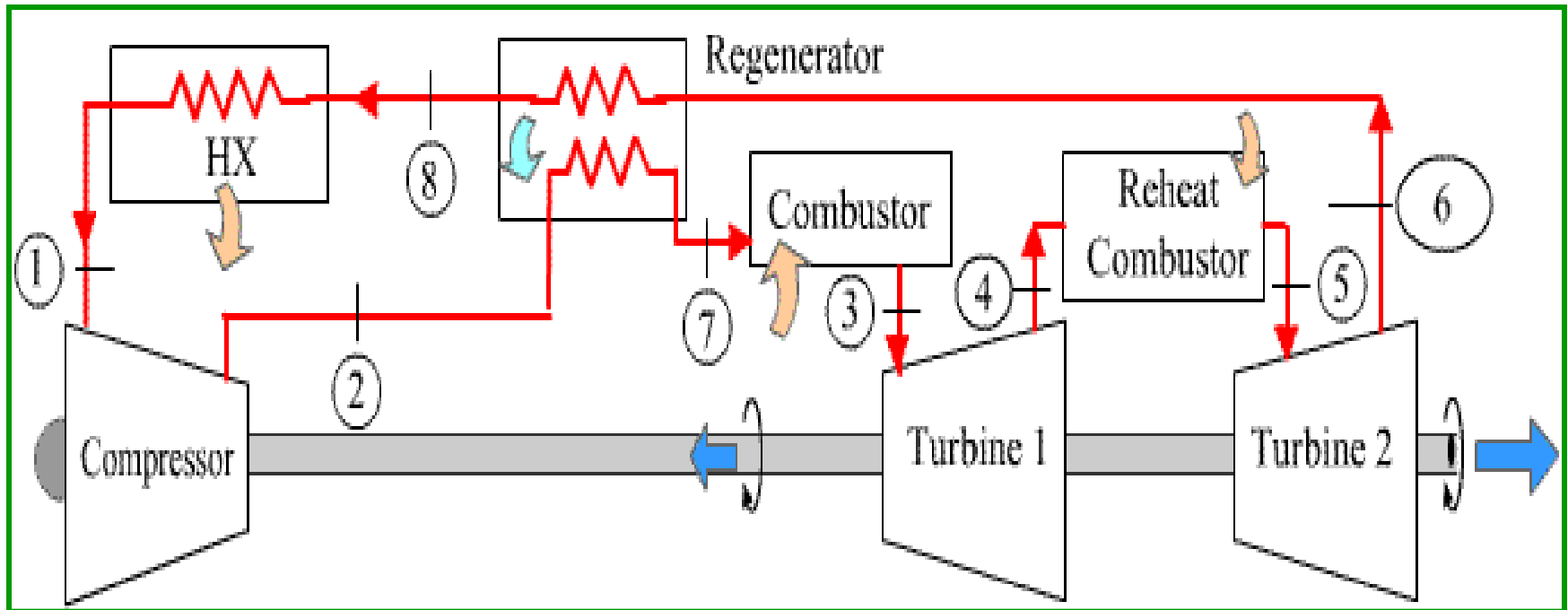
GAS TURBINE POWER PLANT

3.6 - (Regeneration + Reheating)

This system consist of a **compressor** and **two turbines** (**HP & LP**) with :

- 1 – **combustion chamber** between the compressor and the first (HP) turbine.
- 2 – **re-heater** between the two turbines.
- 3 – **regenerator** between the second (LP) turbine and the compressor.

Such system is illustrated in fig.9



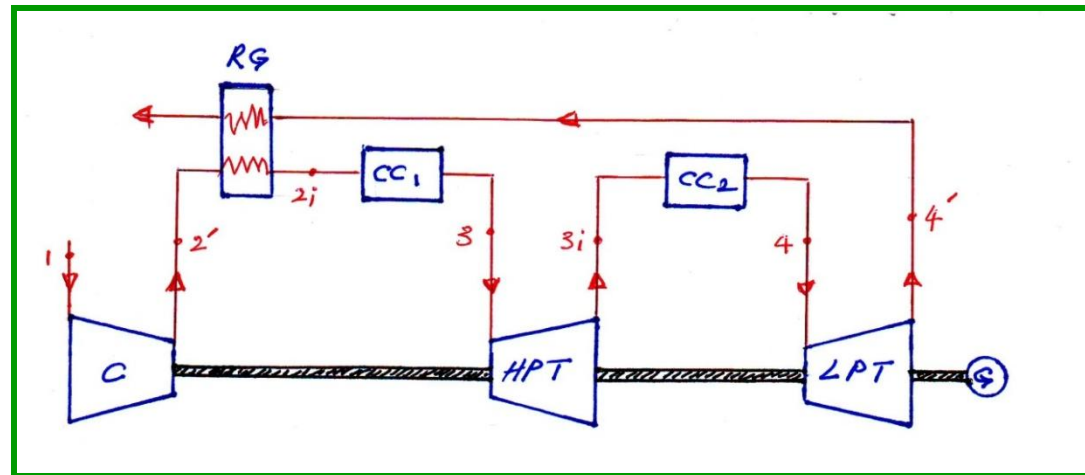
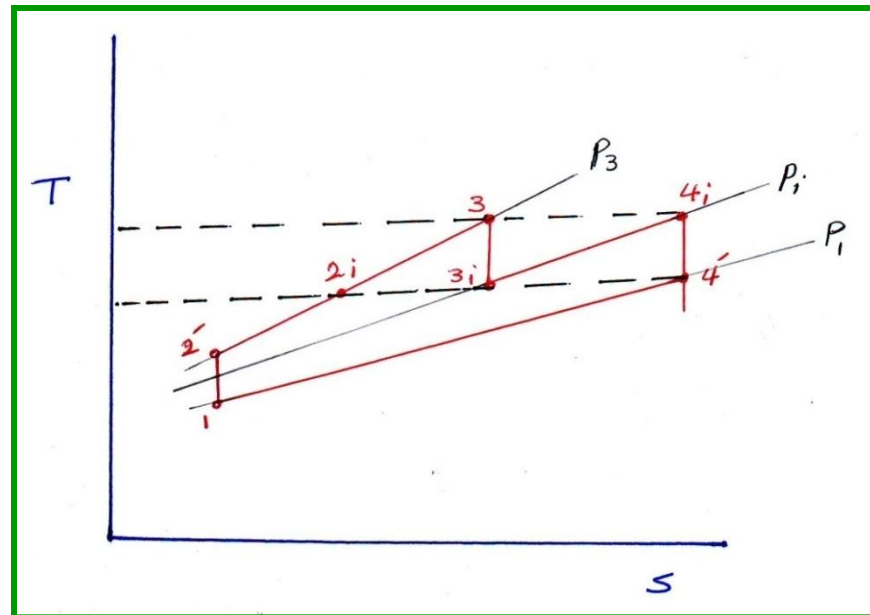


Fig. 9



Remarks on fig.9

The schematic diagram notations are as follows :

C : compressor

HPT : high pressure turbine

LPT : low pressure turbine

CC1 : combustion chamber

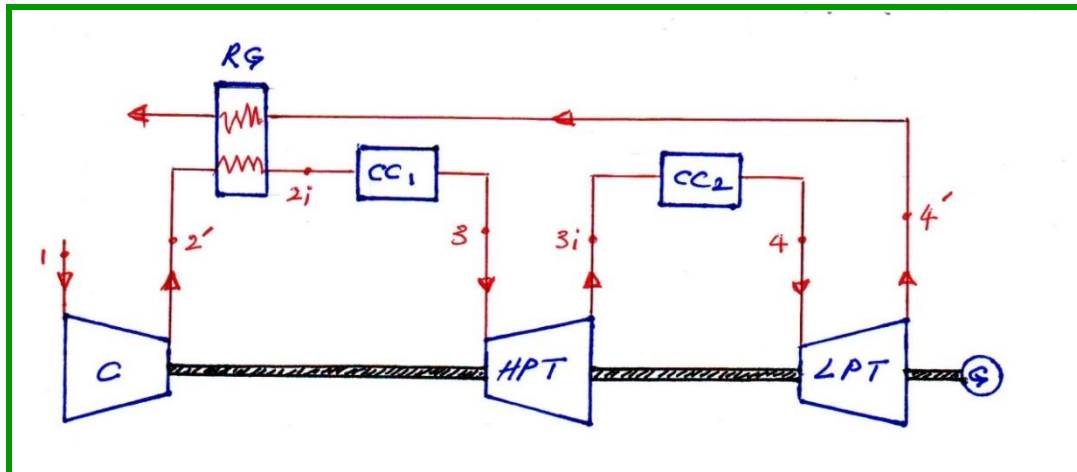
CC2 : re-heater

RG : regenerator

G : electric generator

The T-s diagram of fig.9 shows that the temperature drop across the turbines are equal such that :

$$T_3 - T_{3i} = T_{4i} - T_{4'}$$



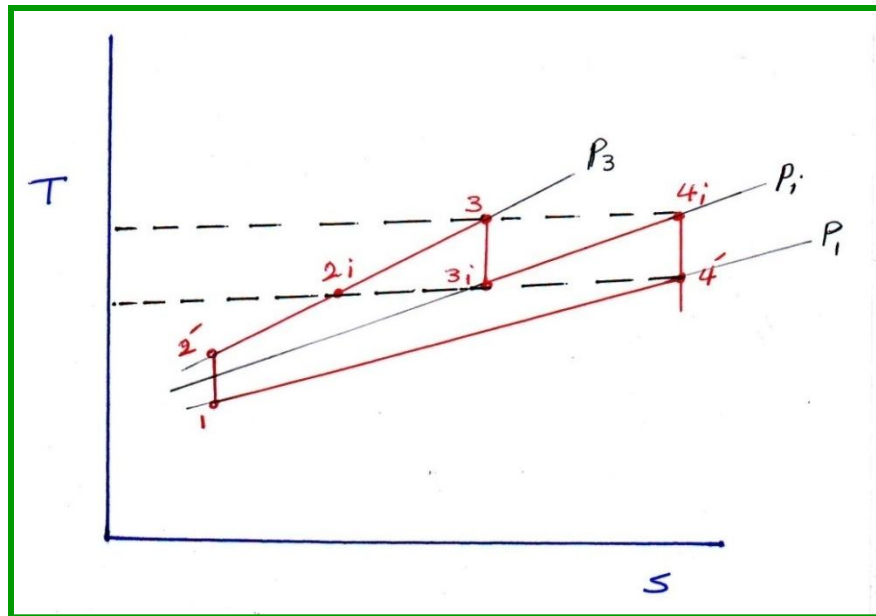
work

The work is the same as in the reheat cycle, which was expressed as:

$$\text{Work o/p} = C_p [(T_3 - T_{3i}) + (T_{4i} - T_{4'}) - (T_{2'} - T_1)]$$

Where the part of the cycle responsible to produce work consist in both cycles of the same components, i.e

CC1 + HPT + CC2 + LPT



Thermal efficiency

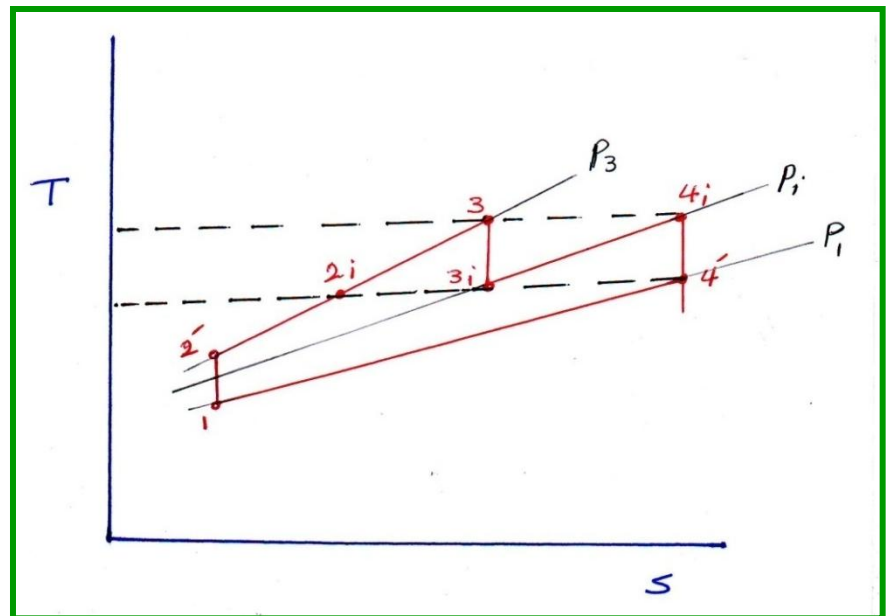
Thermal eff. is improved due to that the compressed air temperature (T_{2i}) is increased by regeneration action, where as shown in the T-s diagram of fig.9

$$T_{2i} > T_2$$

and hence heating from (T_{2i}) to (T_3) only that take place in CC1

And therefore the thermal eff. is

$$\eta_{th} = 1 - \frac{(T_2 - T_1)}{2(T_3 - T_{3i})}$$



For optimum conditions

$$T_{2i} = T_{3i} = T_{4-}$$

$$\eta_{th} = 1 - \frac{(T_{2-} - T_1)}{2(T_3 - T_{3i})} \quad \text{eq.a}$$

Consider the term $(T_{2-} - T_1)$

$$\begin{aligned} (T_{2-} - T_1) &= T_1 \left(\frac{T_{2-}}{T_1} - 1 \right) \\ &= T_1 (r_{p^n} - 1) \quad \text{eq.b} \end{aligned}$$

Similarly consider the term $(T_3 - T_{3i})$

$$\begin{aligned} 2(T_3 - T_{3i}) &= 2T_1 \left[\left(\frac{T_3}{T_1} \right) - \left(\frac{T_{3i}}{T_1} \right) \right] \\ &= 2T_1 \left(\frac{T_3}{T_1} \right) \left[(1) - \left(\frac{T_1}{T_3} \right) \left(\frac{T_{3i}}{T_1} \right) \right] \\ &= 2T_1 \left(\frac{T_3}{T_1} \right) \left[(1) - \left(\frac{T_{3i}}{T_3} \right) \right] \quad \text{eq.c} \end{aligned}$$

The term $(T_{3i}/T_3) = 1/r_{p_3}^n$

But as shown previously in the reheat cycle that $r_{p1} = \sqrt{r_p}$

For (W_{max})

$\Rightarrow \Rightarrow$ r_p of HPT = $\sqrt{\text{total } r_p}$

Then

$$1/r_{p_3} = 1/\sqrt{r_p}$$

then $(T_{3i}/T_3) = 1/r_p^n = (1/\sqrt[n]{r_p})^n = (1/r_p)^{n/2}$

Sub in eq.b to get

$$\begin{aligned} 2(T_3 - T_{3i}) &= 2T_1 (T_3/T_1) [(1) - (T_{3i}/T_3)] \\ 2(T_3 - T_{3i}) &= 2T_1 (T_3/T_1) [(1) - ((1/r_p)^{n/2})] \end{aligned} \quad \text{eq.c}$$

Sub.(eq.b & eq.c) in eq.a

$$\eta_{th} = 1 - \frac{(T_2 - T_1)}{2(T_3 - T_{3i})} \quad \text{eq.a}$$

$$(T_2 - T_1) = T_1 ((r_p^n) - 1) \quad \text{eq.b}$$

$$2(T_3 - T_{3i}) = 2T_1 (T_3/T_1) [(1) - ((1/r_p)^{n/2})] \quad \text{eq.c}$$

To obtain

$$\eta_{th} = 1 - \frac{T_1 ((r_p^n) - 1)}{2T_1 (T_3/T_1) [(1) - ((1/r_p)^{n/2})]}$$

Finally

$$\eta_{th} = 1 - \frac{[(r_p^n) - 1]}{2\left(\frac{T_3}{T_1}\right)\left[1 - \left(\frac{1}{r_p}\right)^{\frac{n}{2}}\right]}$$

Therefore, it can be noted that

$$\eta_{th} = f (r_p , (T_3/T_1) , \gamma)$$

Chapter Three

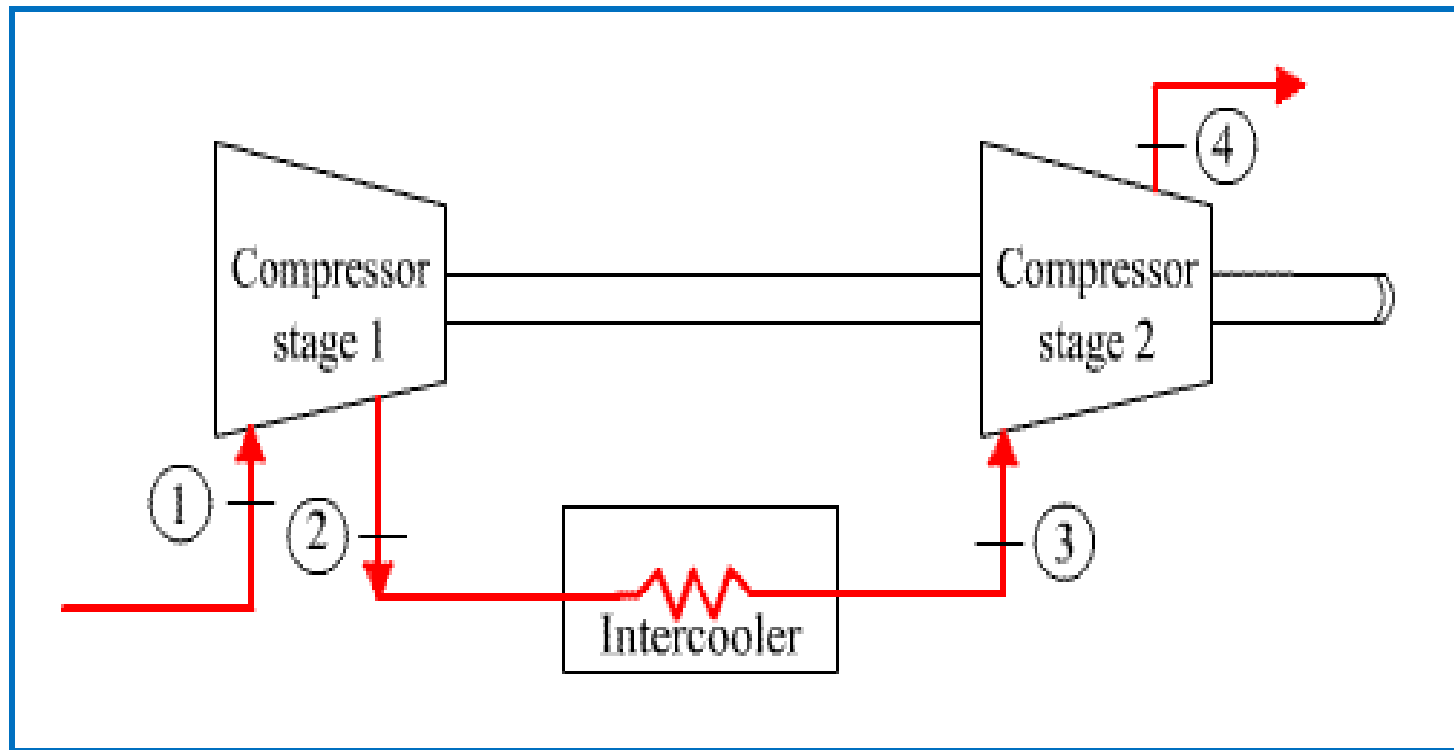
GAS TURBINE POWER PLANT

3.7 - Inter - cooling

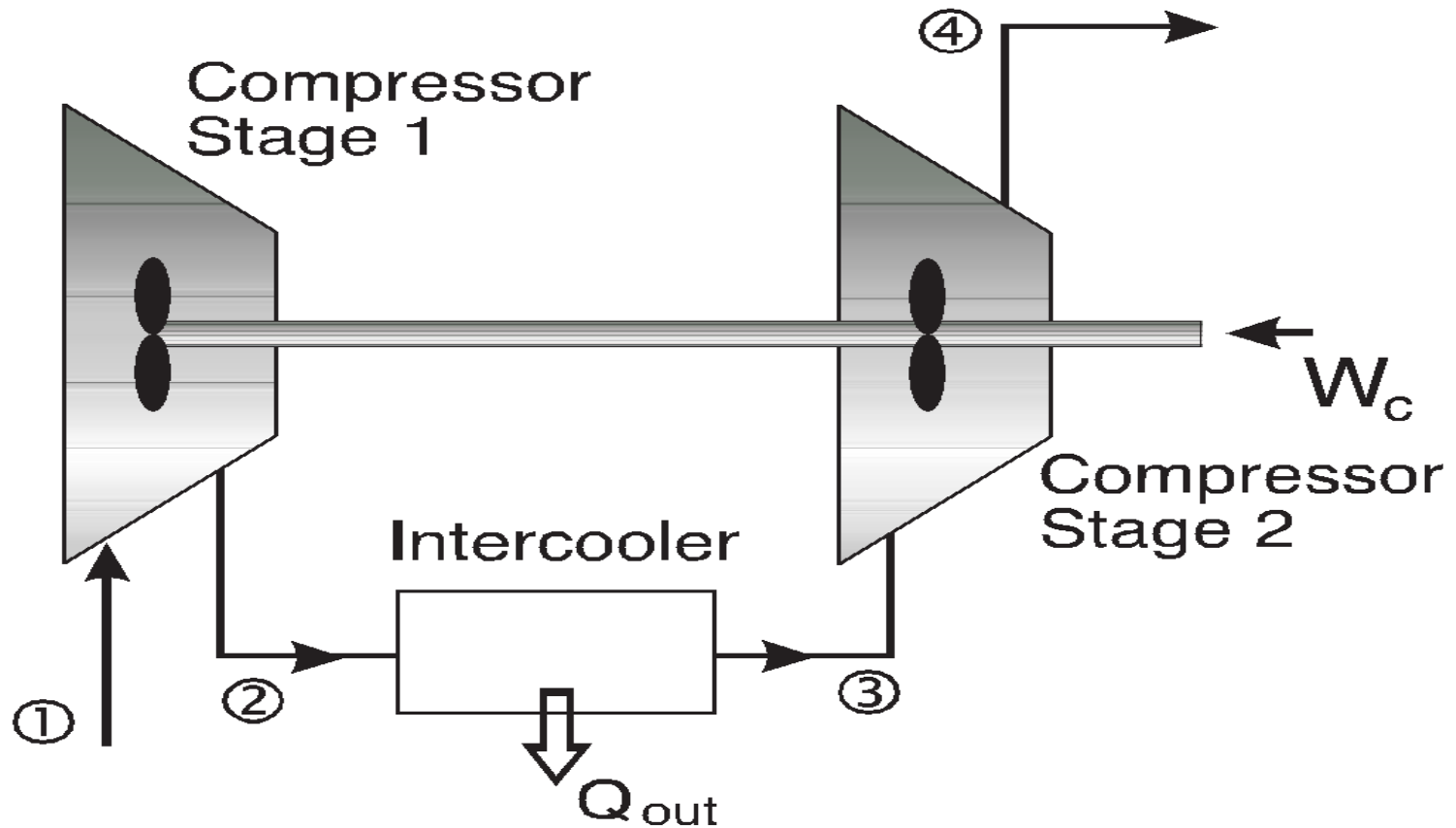
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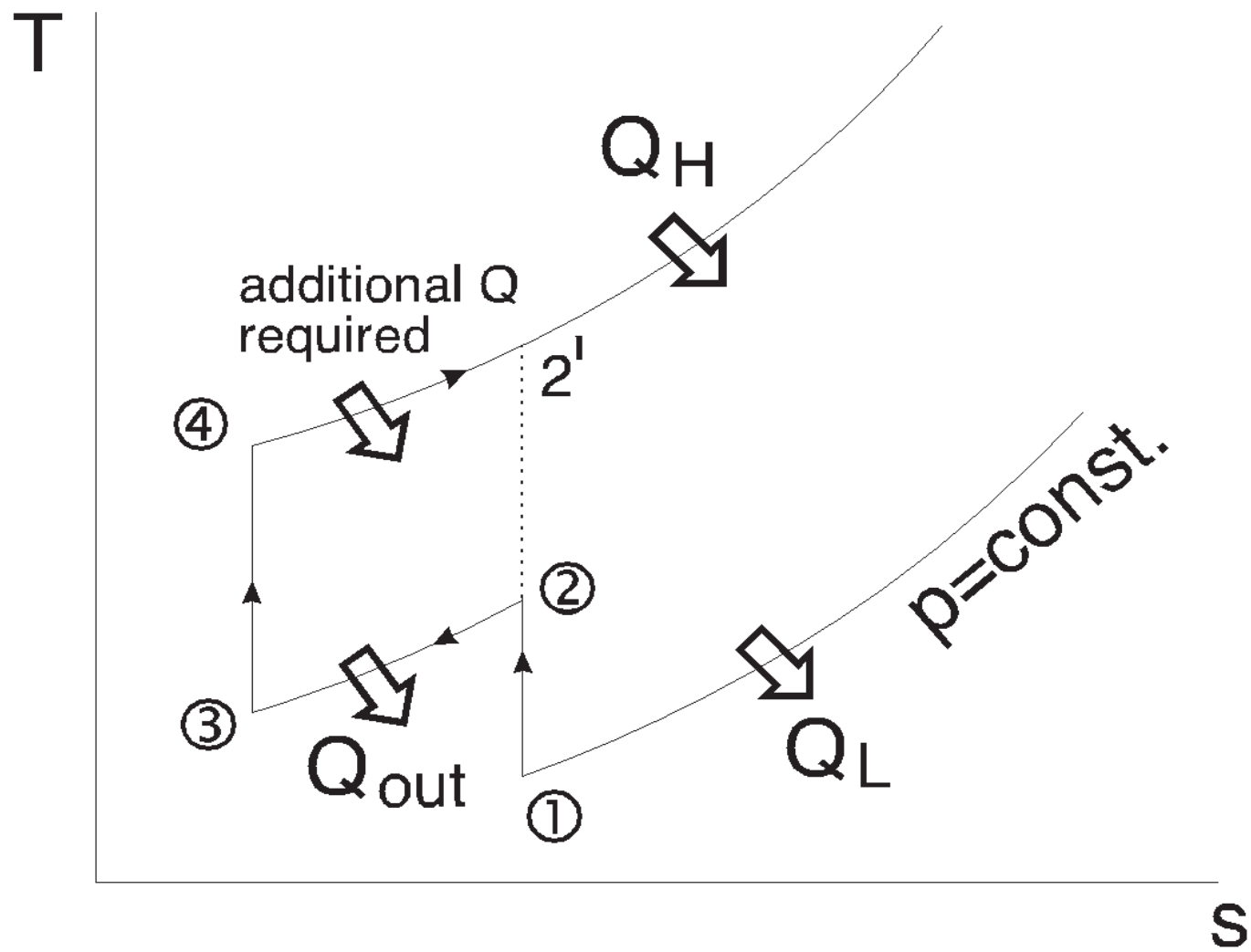
- During any compression process, the air temperature and pressure will be increased depending on the encasement volume as previously seen in the air standard “ otto – diesel – dual “ cycles.
- Therefore, at the end of compression the working fluid temperature is increased say from (T_1) to (T_2) .
- In some power generation system of a large scale plant, single stage compression may not be enough, and therefore multi-stage compression will be required.

In a multi-stage compression the outlet temperature from the first stage will be the inlet to the next stage, and so **compressive heating of the working fluid will keep raising the outlet temperature of each stage**, which eventually reach an undesirable level and causes a marked reduction in the overall system performance, which in this case a wasteful energy may economically be fairly costly. This is why **inter-cooling** between compression stages is used to keep (T_{in}) to any stage almost equal to that inlet to the first stage.



Compression with Intercooling

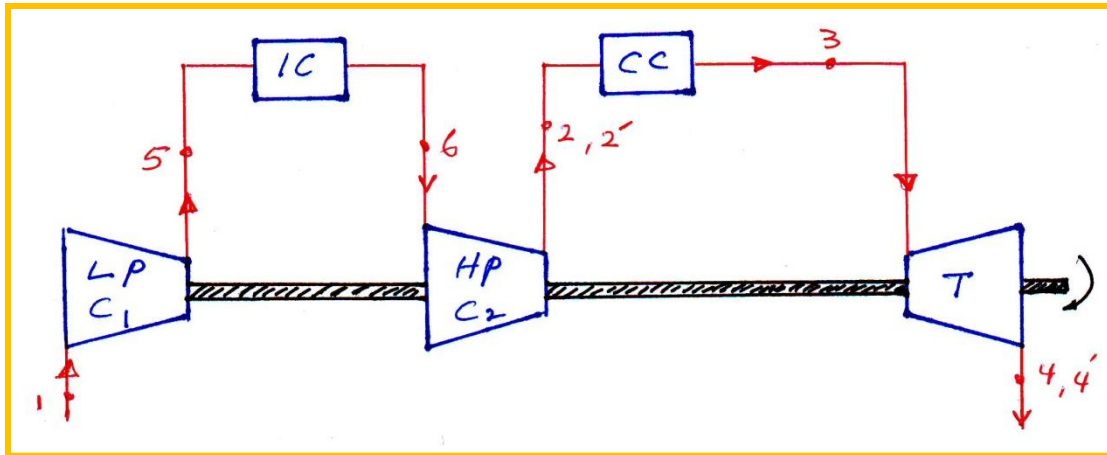


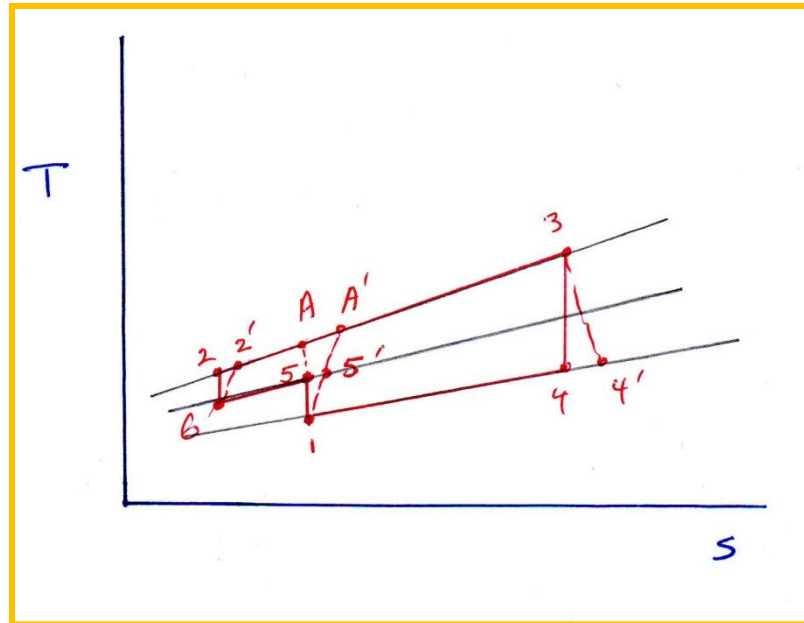
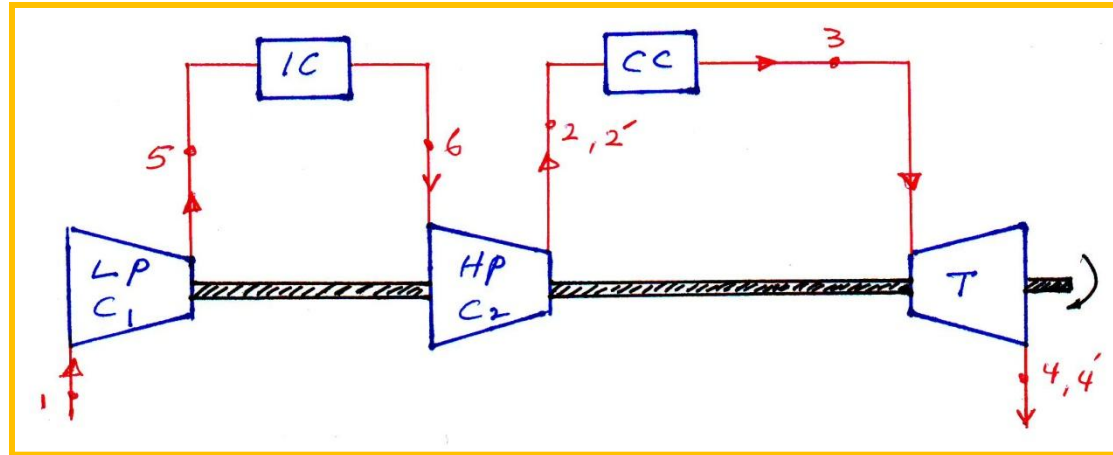


Two – stage compression

Consider the system shown schematically in (fig. 10), where the actual processes are denoted as follows :

1 → 5 → → LP compressor
5 → 6 → → inter-cooler
→ → HP compressor-6 → 2
→ 3 → → combustion chamber-2
→ → turbine-3 → 4





The ideal cycle flow the state points

1 – 5 – 6 – 2 – 3 – 4 – 1

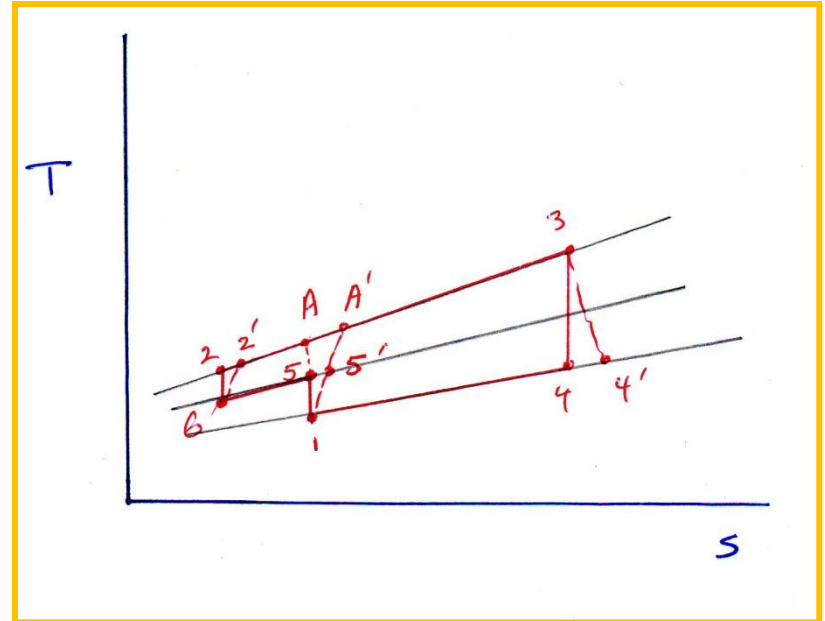
It is useful to note the cycle without inter-cooling for further analysis, such cycle is denoted as follows :

I–ideal no-intercooling

→ **1 – A – 3 – 4 – 1**

II–actual no-intercooling

→ **1 – A' – 3 – 4' – 1**



Work i/p to compressor

1 – work i/p with inter-cooling (W_{ic})

$$W_{ic} = C_p (T_{5'} - T_1) + C_p (T_{2'} - T_6)$$

2 – work i/p with no-intercooling (W_{nic})

$$W_{nic} = C_p (T_{A'} - T_1)$$

Rearranging in reference with T-s diagram shown in fig.

$$W_{nic} = C_p (T_{5'} - T_1) + C_p (T_{A'} - T_{5'})$$

Note that Eqs.1 & 2 differ only in the $(T_{5'} - T_6)$ and $(T_{A'} - T_{5'})$ second terms

and

Since the constant pressure lines diverge from left to right, which means that the vertical distance between them increases in the direction from left to right, resulting in that the following vertical line sectors are related as :

$$(T_{2'} - T_6) < (T_{A'} - T_{5'})$$

And therefore

$$W_{ic} < W_{nic}$$

Conclusion from above is that the work input for a given pressure ratio and mass flow will be reduced by inter-cooling

T-s diagram .. Fig.10

- The following remarks are noted :
- 1- $W_{ic} = \text{minimum}$, when
 - i- the (r_p) is equal in each stage
 - $P_5/P_1 = P_2/P_6 = r_p$
 - ii- air is cooled in the intercooler down to the original temperature.
 - $T_6 = T_1$ this case is known as
 - complete or perfect cooling

2- since (W_{ic}) is reduced , then the (WR) is increased as:

$$WR = (W_t - W_{ic}) / W_t$$

($W_t - W_{ic}$) this the NW output from the system, and it is shown that

$$(NW_{ic} < NW_{nic})$$

3- heat supplied for the same max (T)

$$Q_{ic} = C_p(T_3 - T_2^-)$$

$$Q_{nic} = C_p(T_3 - T_A^-)$$

Therefore

$$(Q_{ic} > Q_{nic})$$

because

$$(T_2^- < T_A^-)$$

4- since $\eta_{th} = NW/Q_{in}$

For intercooling:

($NW_{ic} \uparrow$) and also ($Q_{ic} \uparrow$)

But the magnitude increase in both differ, such that it was in general found that :

$$\eta_{th.ic} < \eta_{th.nic}$$

Ideal cycle

With complete inter-cooling and isentropic condition, the work input to the compressor is :

$$\begin{aligned} W_{ic} &= C_p(T_5 - T_1) + C_p(T_2 - T_6) \\ &= C_p.T_1(T_5/T_1 - 1) + C_p.T_6(T_2/T_6 - 1) \end{aligned}$$

Since

$$T_6 = T_1$$

$$T_5/T_1 = (P_i/P_l)^n$$

$$T_2/T_6 = (P_h/P_i)^n$$

$$n = (\gamma - 1) / \gamma$$

$$(P_i/P_l) = (P_h/P_i) = r_{pi} = \sqrt[n]{r_{p.tot}}$$

The saving in work will depend on the choice of the intercooling pressure (P_i).

By differentiation (dw/dp) and equating to zero, the condition for minimum work is found to be

$$P_i = \sqrt[n]{P_l \cdot P_h}$$

$$(P_i/P_l) = (P_h/P_i) = r_{pi}$$

$$r_{pi} = \sqrt[n]{r_{p.tot}}$$

$$W_{ic} = C_p.T_1(r_p^n - 1) + C_p.T_1(r_p^n - 1)$$

$$W_{ic} = 2 C_p.T_1(r_p^n - 1)$$

Chapter Three

GAS TURBINE POWER PLANT

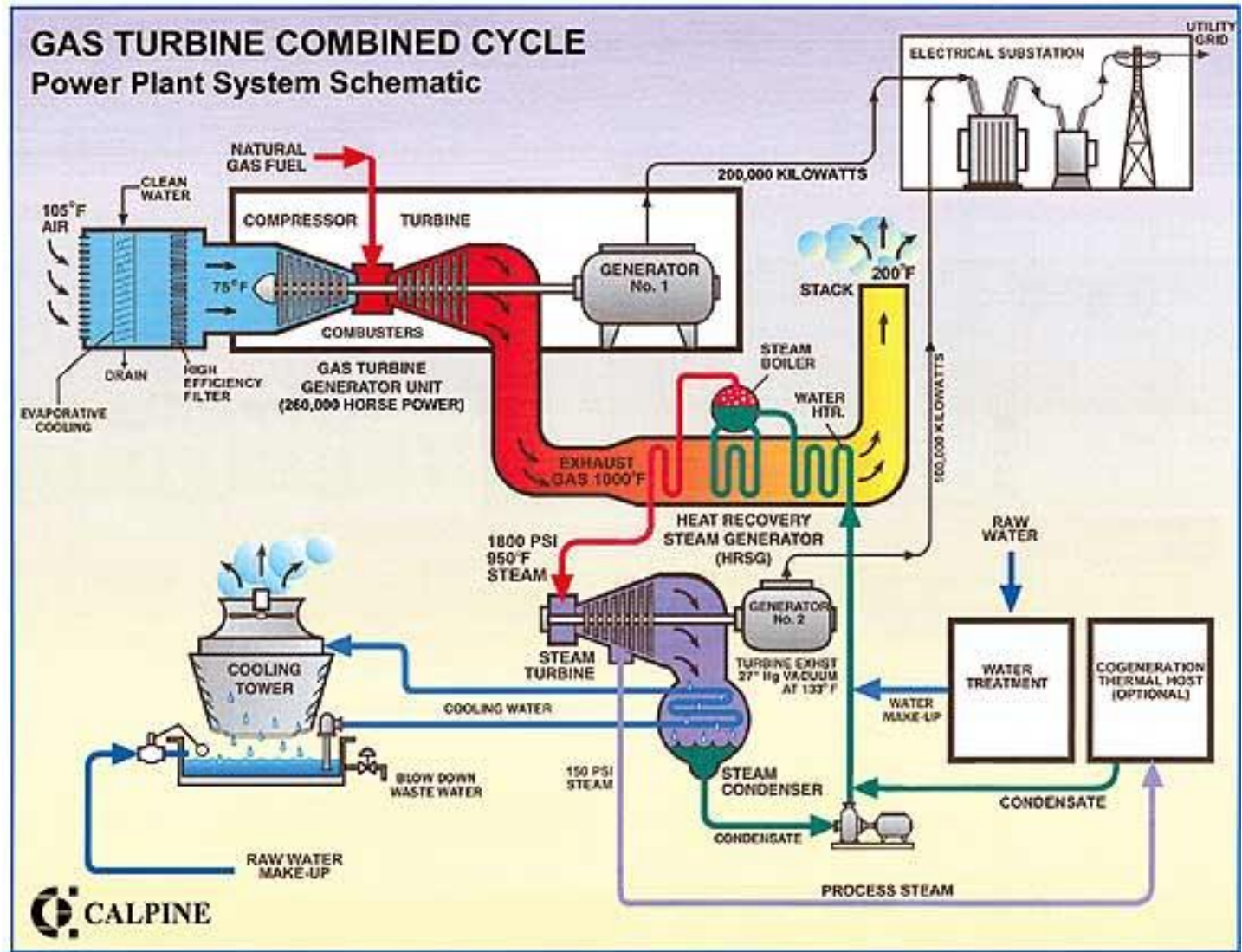
3.8 - Combined cycle

&

Cogeneration

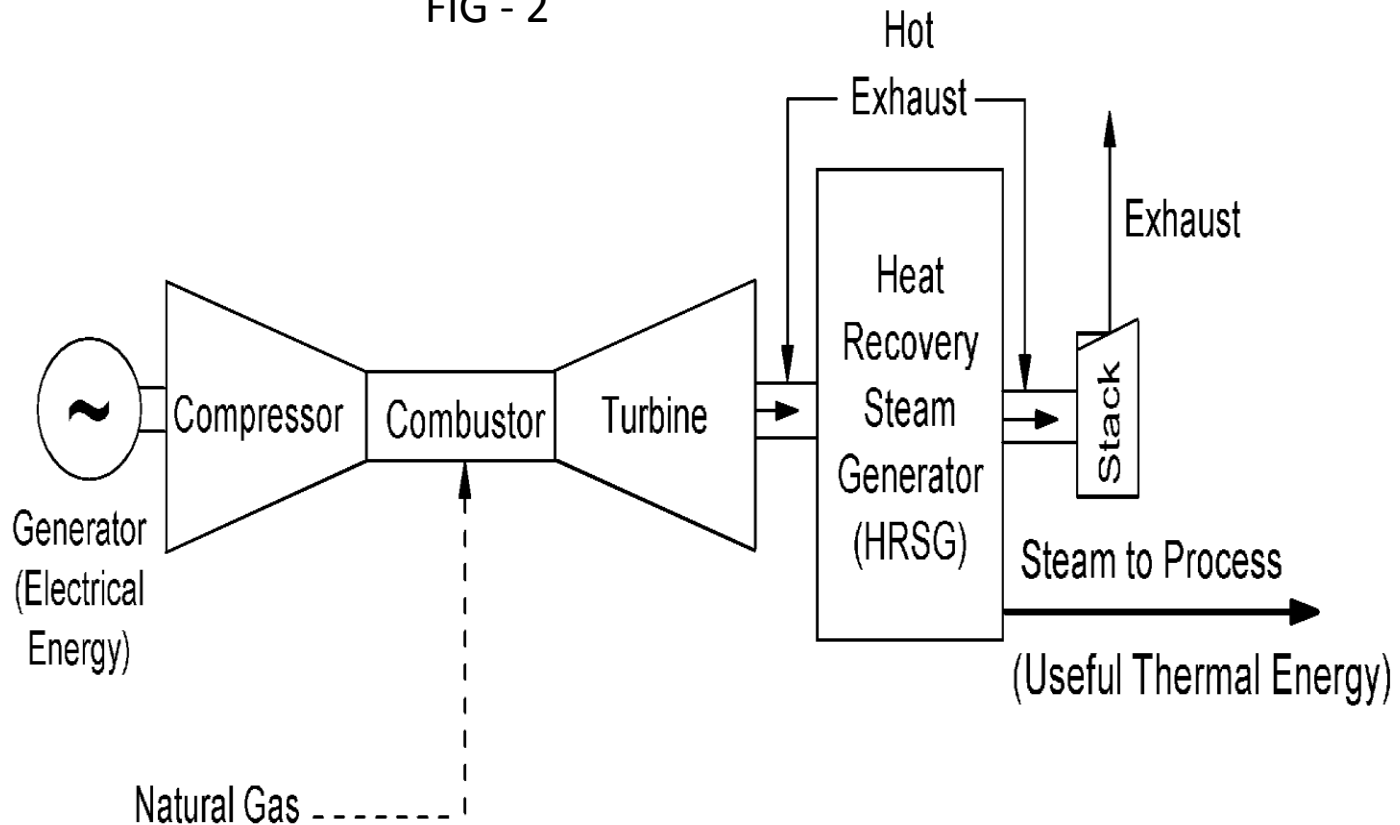
Gas turbine combined cycle

Fig.1



A [Heat Recovery Steam Generator](#) or [HRSG](#) is a **steam boiler** that uses hot exhaust gases from the [gas turbines](#) in a CHP (combined heat and power) plant to heat up water and generate [steam](#). This steam in turn drives a [steam turbine](#) .

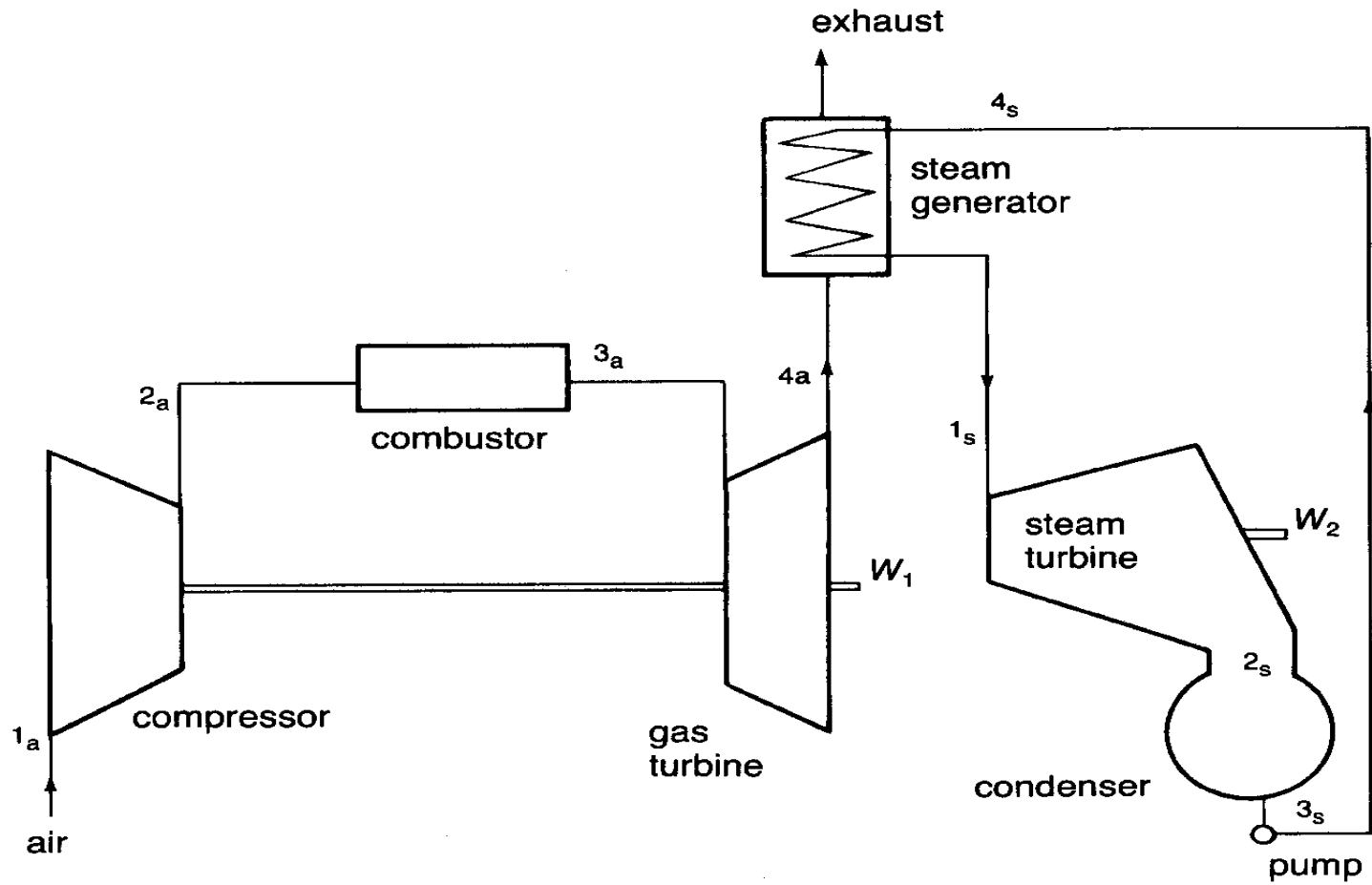
FIG - 2



introduction

- The following general remarks related to the combined cycle are useful to understand the benefit of such system :
- 1- the combined cycle is a union of Brayton and Rankine cycles.
- 2- Brayton cycle is topping while Rankine is bottoming.
- 3- the major components that makes up the combined cycle are :
 - i- gas turbine.
 - ii- heat recovery steam generator (HRSG)
 - iii- steam turbine
- 4- steam turbine utilizes the energy in the gas turbine exhaust gas as it's input energy.

Fig.3



Combined cycle performance

- Referring to fig.3 for notations :
- 1 – gas turbine cycle
- -compressor work (W_c)
- $W_c = m_a (h_{2a} - h_{1a})$
- -turbine work output (W_{tg})
- $W_{tg} = (m_a + m_f)(h_{3a} - h_{4a})$
- -net work (NW)
- $NW_g = W_{tg} - W_c$
- -heat input (Q_{2a3a})
- $Q_{2a3a} = (m_a + m_f)h_{3a} - m_a.h_{2a}$

2 – steam turbine cycle

-pump work (W_p)

$$W_p = m_s (h_{4s} - h_{3s})$$

-turbine work output (W_{ts})

$$W_{ts} = m_s (h_{1s} - h_{2s})$$

Net work (NW_s)

$$NW_s = W_{ts} - W_p$$

-heat input (Q_{4s1s})

$$Q_{4s1s} = m_s (h_{1s} - h_{4s})$$

3 – system performance

-system total work output (W_{tot})

$$W_{tot} = NW_g + NW_s$$

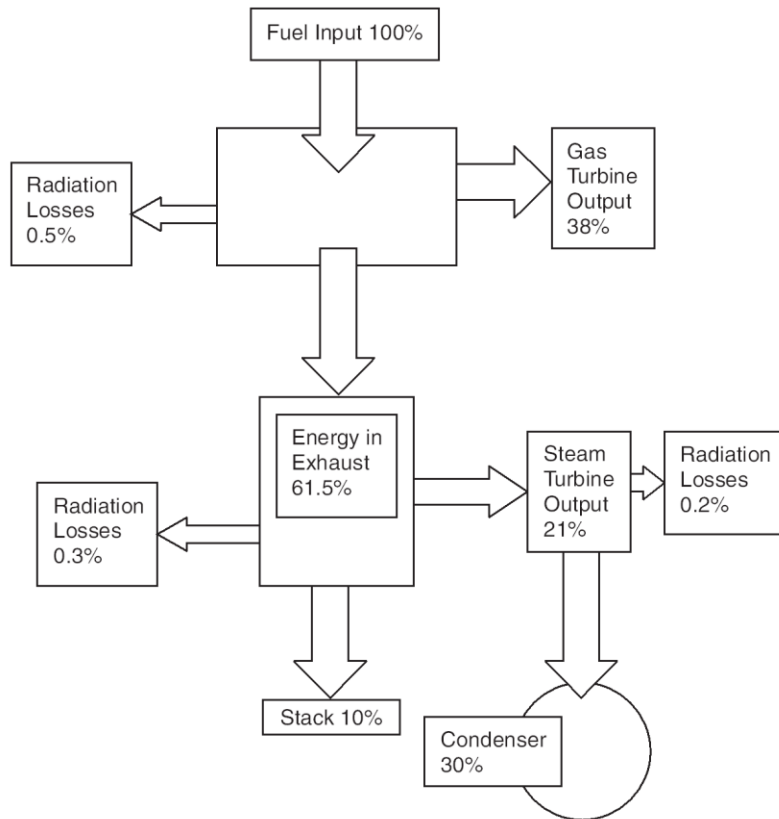
$$= W_{tg} + W_{ts} - W_c - W_p$$

-system thermal efficiency

$$\eta = W_{tot} / (m_f \cdot LHV)$$

Energy distribution

- Generally, the energy supplied in the combined cycle is usually related to two operating conditions :
- 1- design operating condition (full load) where (60%) of the system power is produced by the gas turbine cycle, while (40%) comes from the steam turbine cycle.
- 2- below (50%) of the design operating conditions, where (40%) from each of the two cycles is supplied.



- Due to various losses encountered in the system under actual operating conditions, the shown diagram shows the energy distribution as a percentage of the total energy input from fuel.

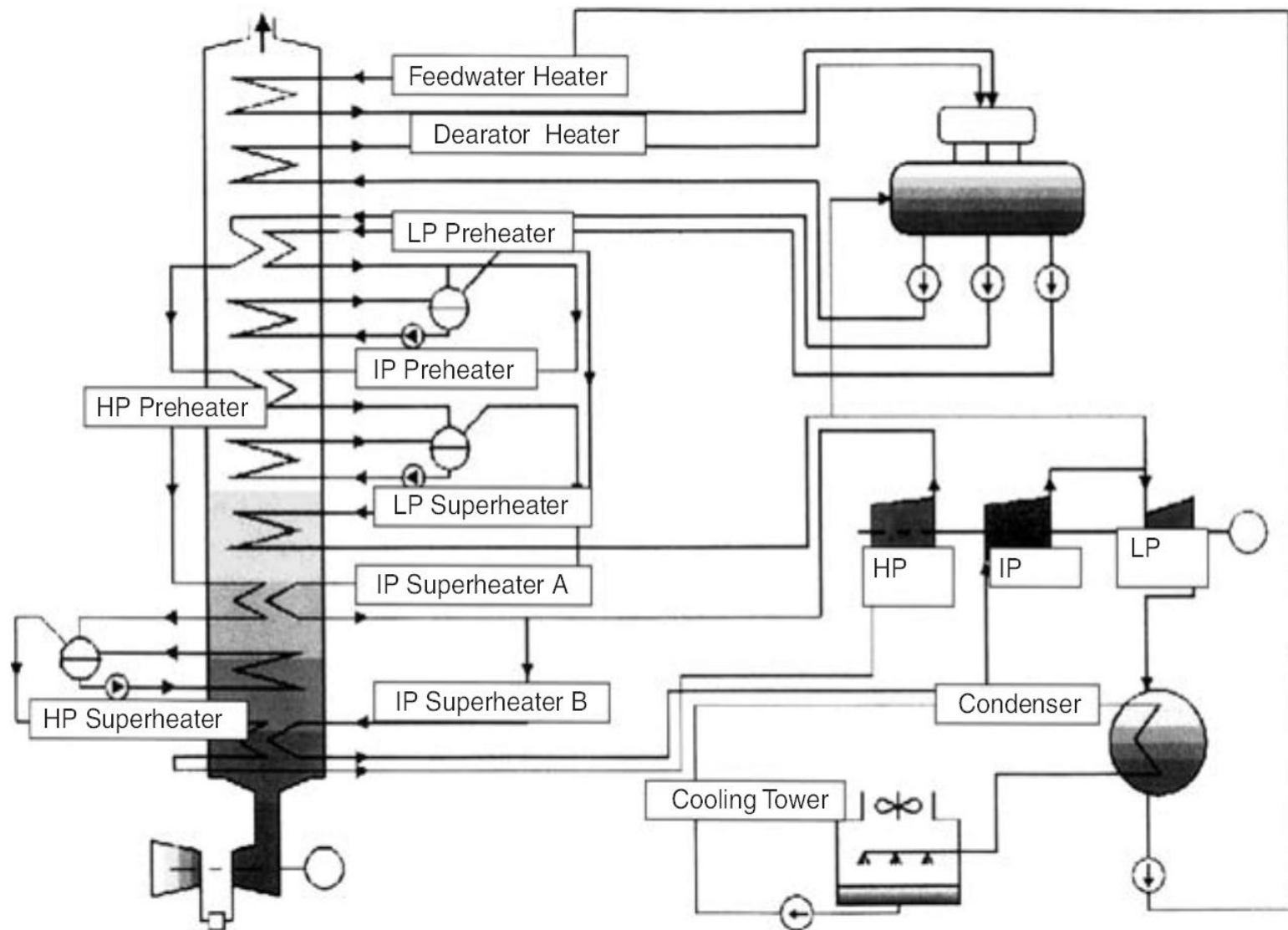
Pinch Point

An important performance parameter is the temperature difference between the evaporator outlet temperature on the steam side, and that on the exhaust gas side. This temperature difference is called the “Pinch Point”.

Ideally, the lower the pinch point the more heat recovered, but calls for more surface area, and consequently, increases the back pressure and cost.

Also, excessively low pinch point, can mean inadequate steam production if the exhaust gas is low in energy (low mass flow or low exhaust gas temperature).

General guide line call for a pinch point range of $(8 - 22)^{\circ}\text{C}$



Large scale system

fig.4

The steam turbines in most of the large power plants are at a minimum divided into two major sections the High Pressure Section (HP) and the Low Pressure Section (LP). In some plants, the HP section is further divided into a High Pressure Section and an Intermediate Pressure Section (IP). The HRSG is also divided into sections corresponding with the steam turbine. The LP steam turbine's performance is further dictated by the condenser backpressure, which is a function of the cooling and the fouling.

The efficiency of the steam section in many of these plants varies from 30–40%. To ensure that the steam turbine is operating in an efficient mode, the gas turbine exhaust temperature is maintained over a wide range of operating conditions. This enables the HRSG to maintain a high degree of effectiveness over this wide range of operation.

In a combined cycle plant, high steam pressures do not necessarily convert to a high thermal efficiency for a combined cycle power plant. Expanding the steam at higher steam pressure causes an increase in the moisture content at the exit of the steam turbine. The increase in moisture content creates major erosion and corrosion problems in the later stages of the turbine. A limit is set at about 10% (90% steam quality) moisture content.

Gas turbine cogenerative cycle

As we've studied in the steam power plant, cogeneration is actually an application for utilizing surplus and waste heat energy to a further useful output of fairly low level heat energy requirement.

Therefore, the followings is repeated statements of specific importance.

Cogeneration (also known as **combined heat and power, CHP**) is the use of a [heat engine](#) or a [power station](#) to simultaneously generate both [electricity](#) and useful [heat](#). It is one of the most common forms of [energy recycling](#)

Conventional gas turbine power plants emit the heat created as a by-product of electricity generation into the natural environment through **flue gas**. By contrast **CHP** captures the by-product heat for domestic or industrial **heating purposes**, either very close to the plant, or as hot water for district heating with temperatures ranging from approximately 80 to 130 °C. This is also called Combined Heat and Power District Heating or CHPDH. Small CHP plants are an example of decentralized energy

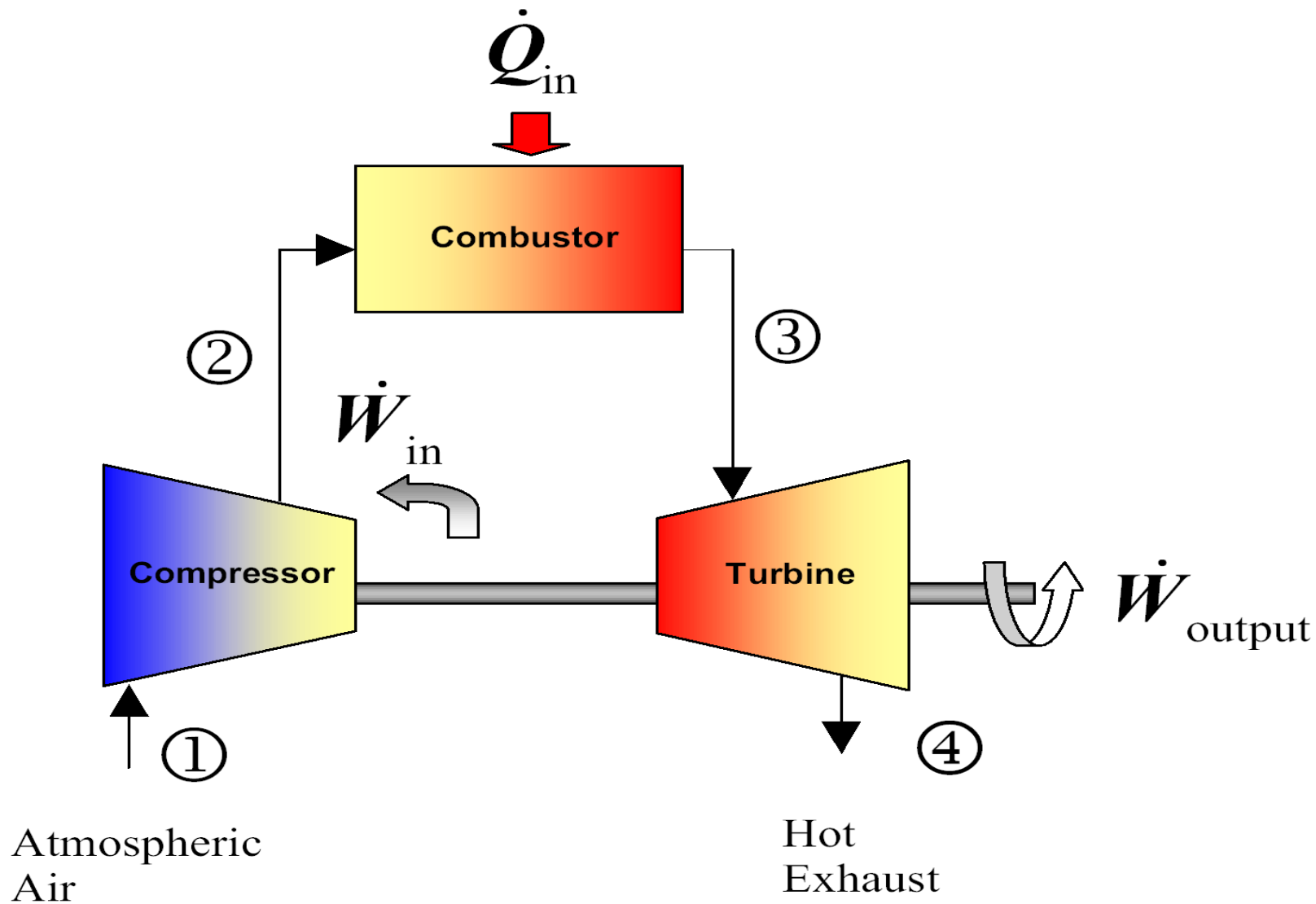
Cogeneration is a [thermodynamically efficient](#) use of [fuel](#). In separate production of electricity some energy must be rejected as [waste heat](#), but in cogeneration this [thermal energy](#) is put to good use.

[Gas turbine power](#) plants in general, do not convert all of their thermal energy into electricity. In most heat engines, a bit more than half is lost as excess heat . By capturing the excess heat, CHP uses heat that would be wasted in a conventional [power plant](#), potentially reaching an [efficiency](#) of up to 89%, compared with 55% for the best conventional plants. This means that less fuel needs to be consumed to produce the same amount of useful energy.

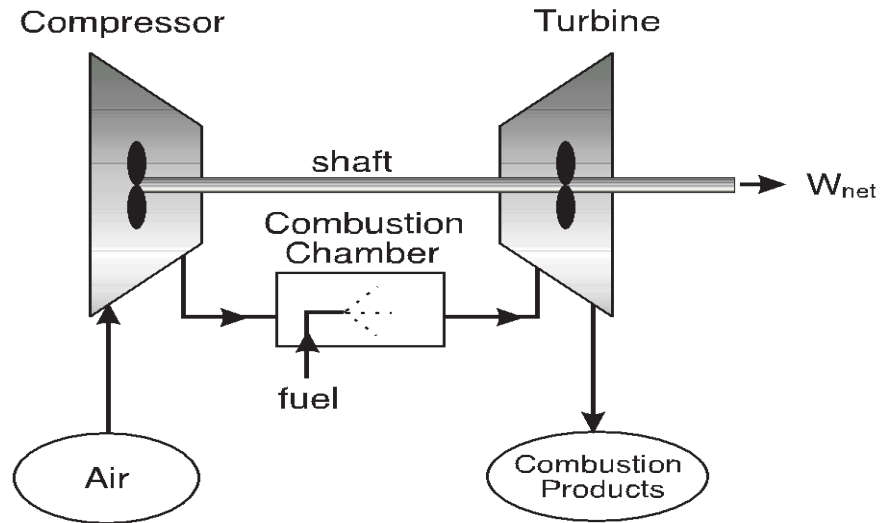
Chapter 3

GAS TURBINE POWER PLANT

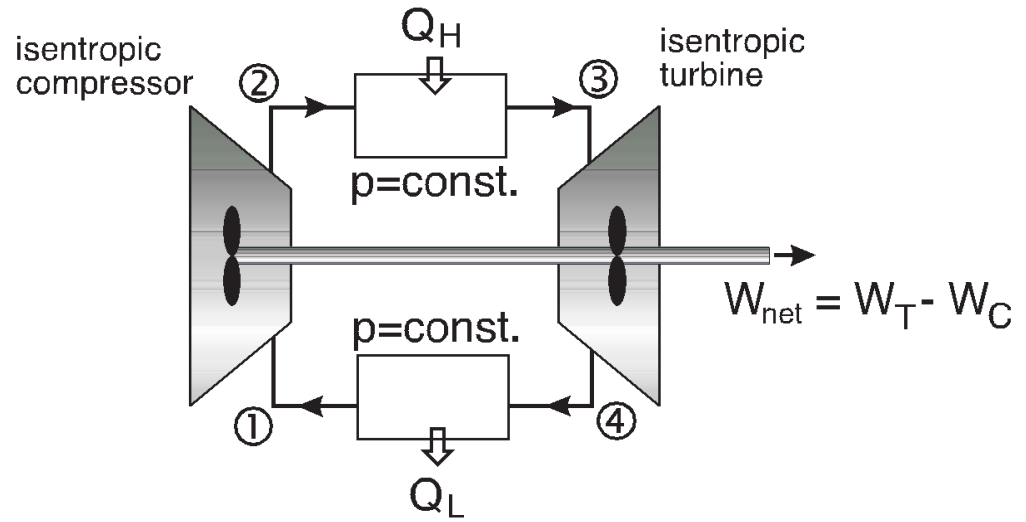
3.9 - Cycle configurations

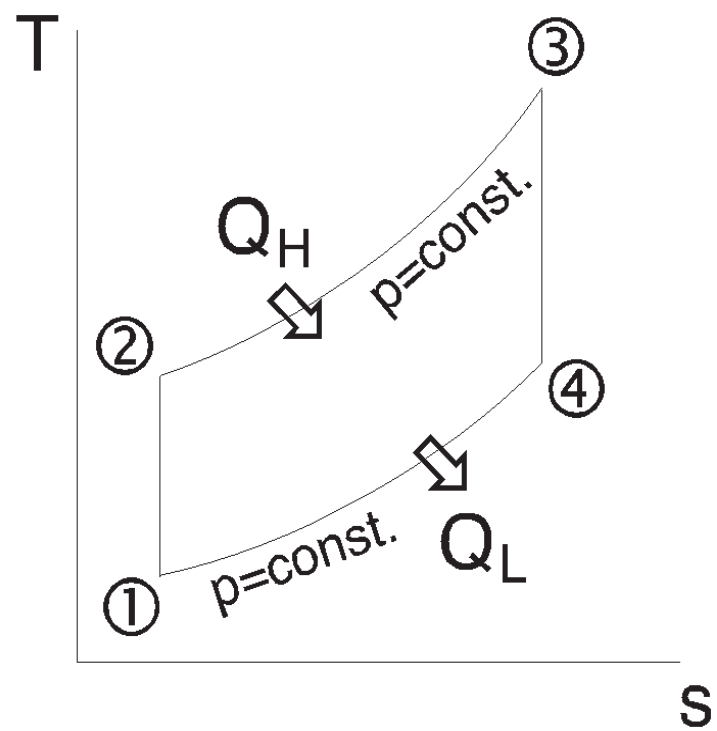
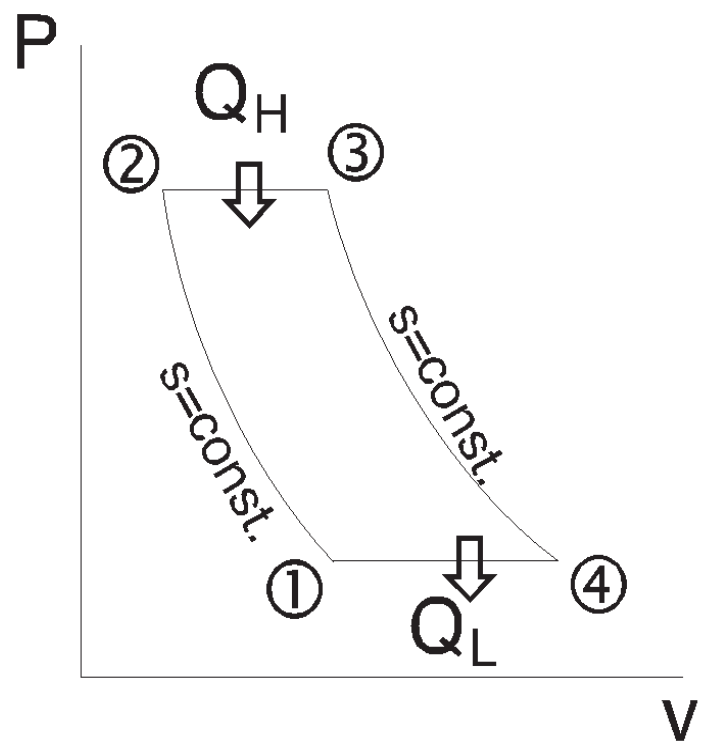


Standard open cycle

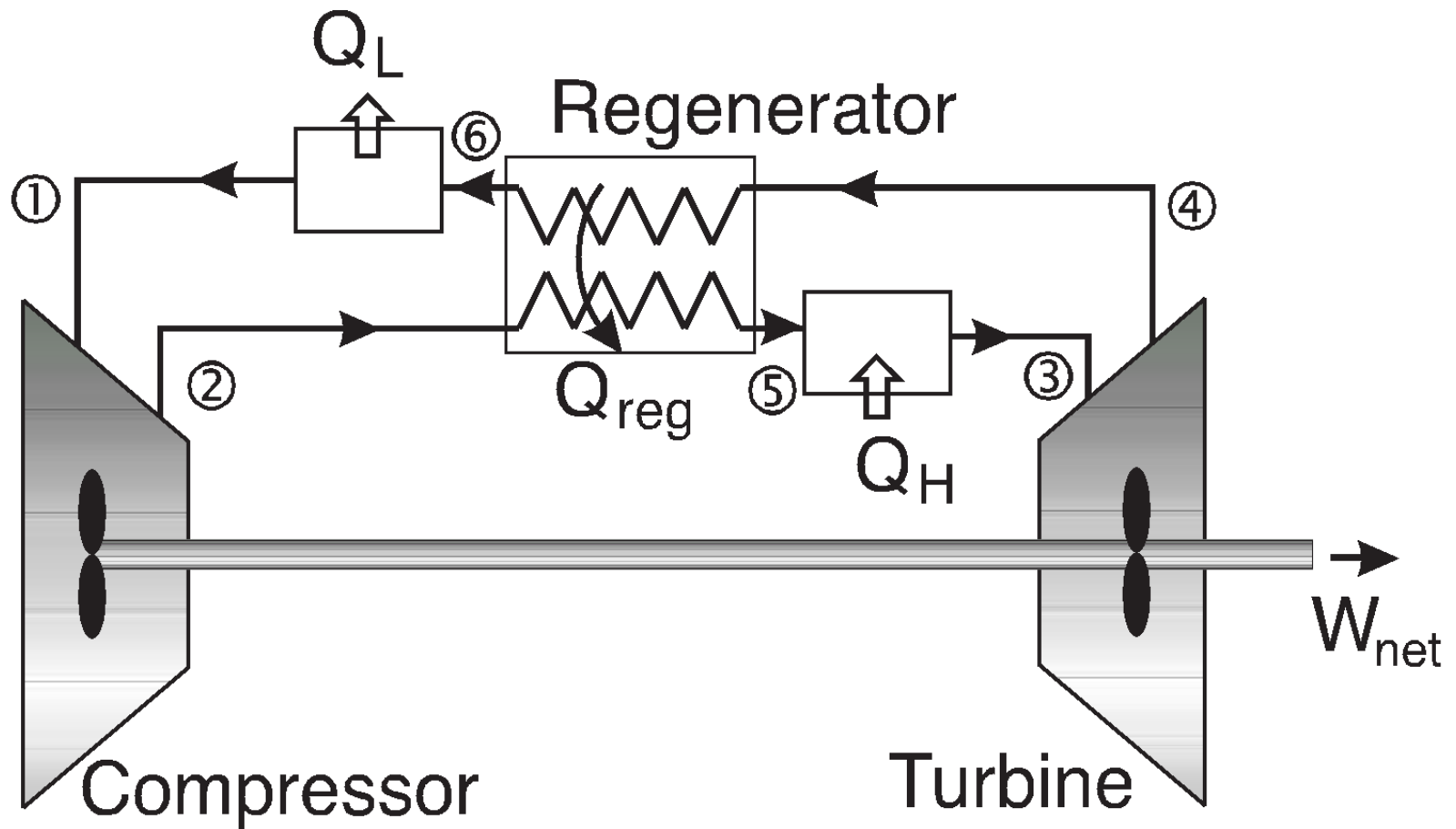


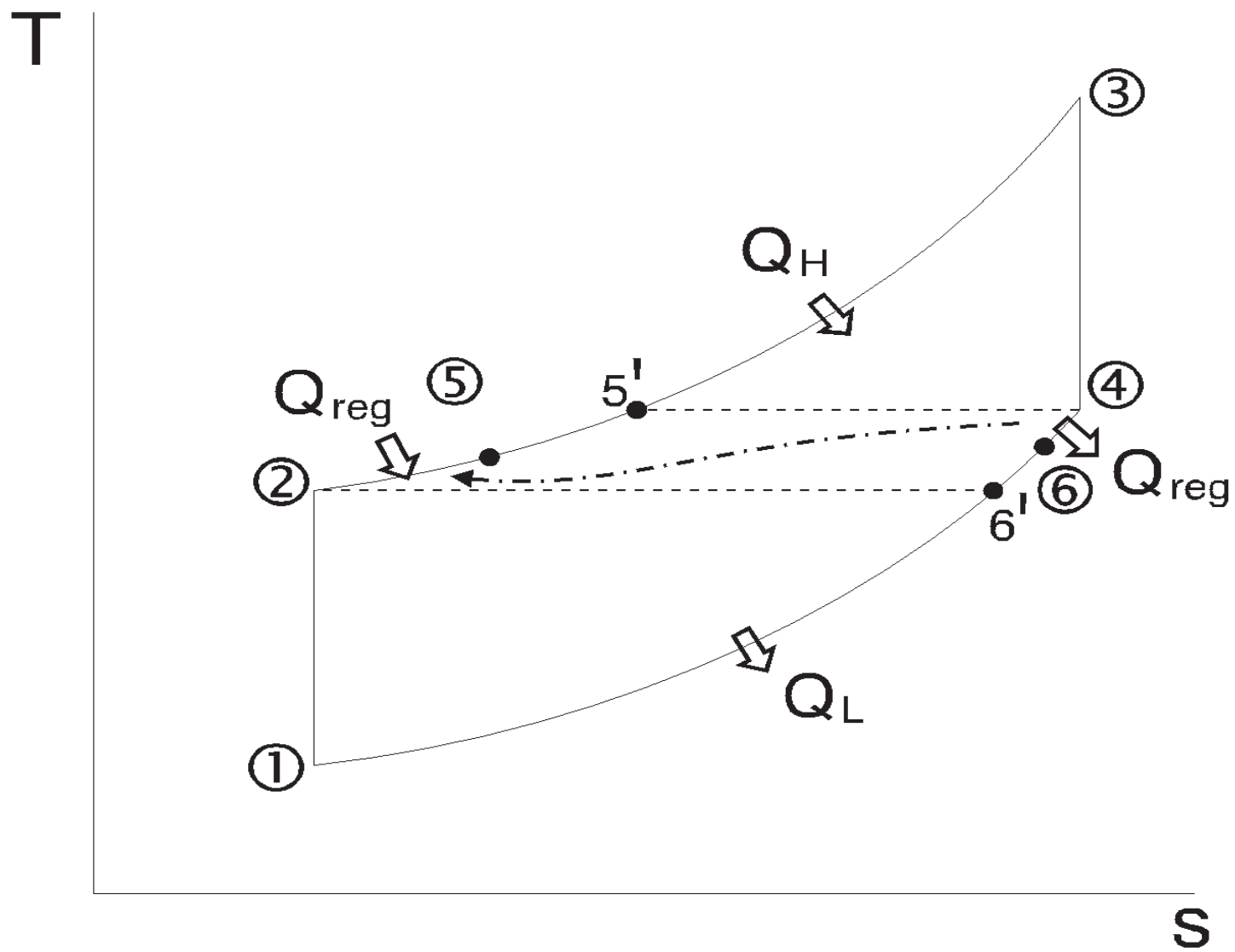
Standard closed cycle



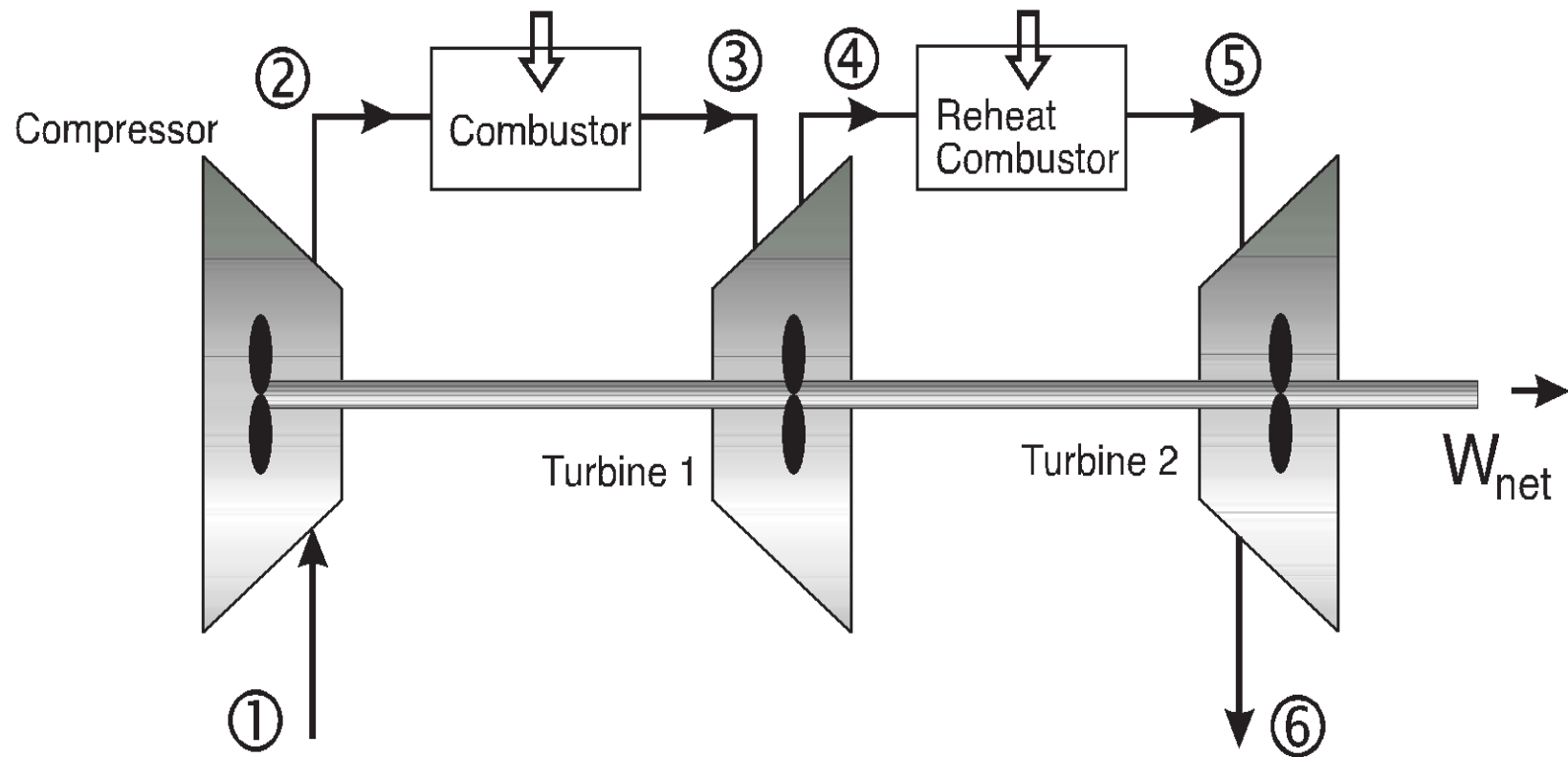


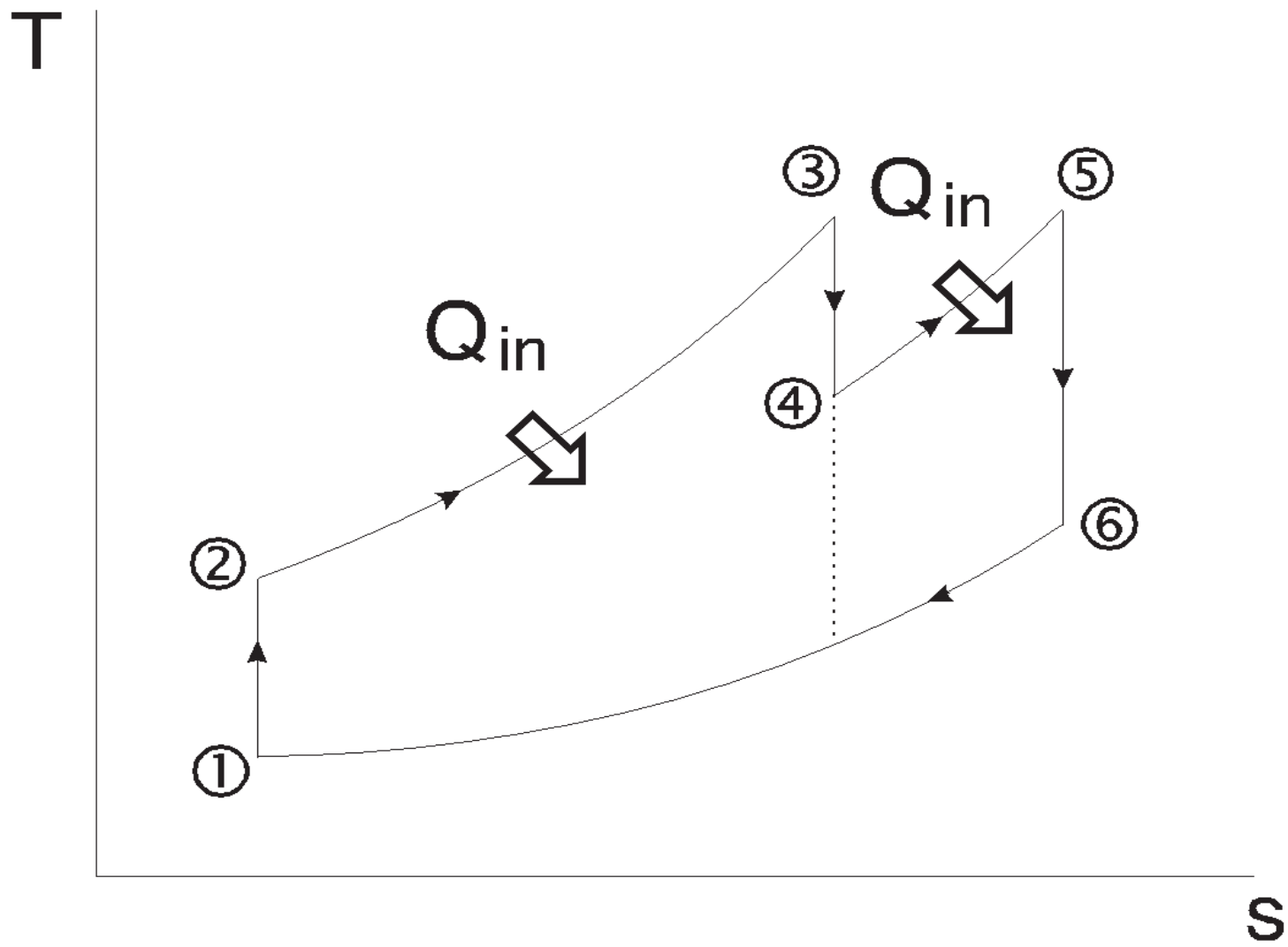
Brayton Cycle with Regeneration



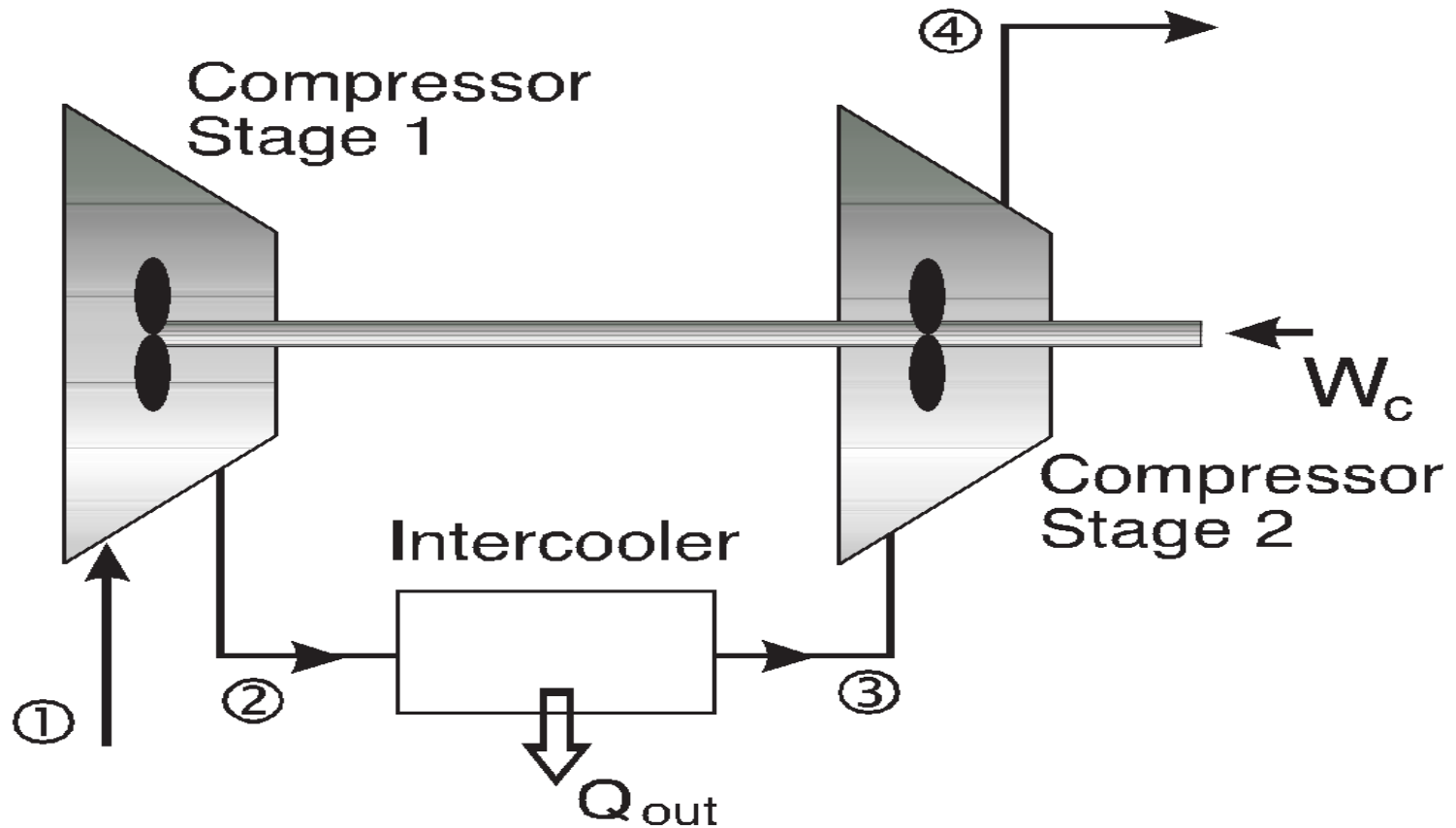


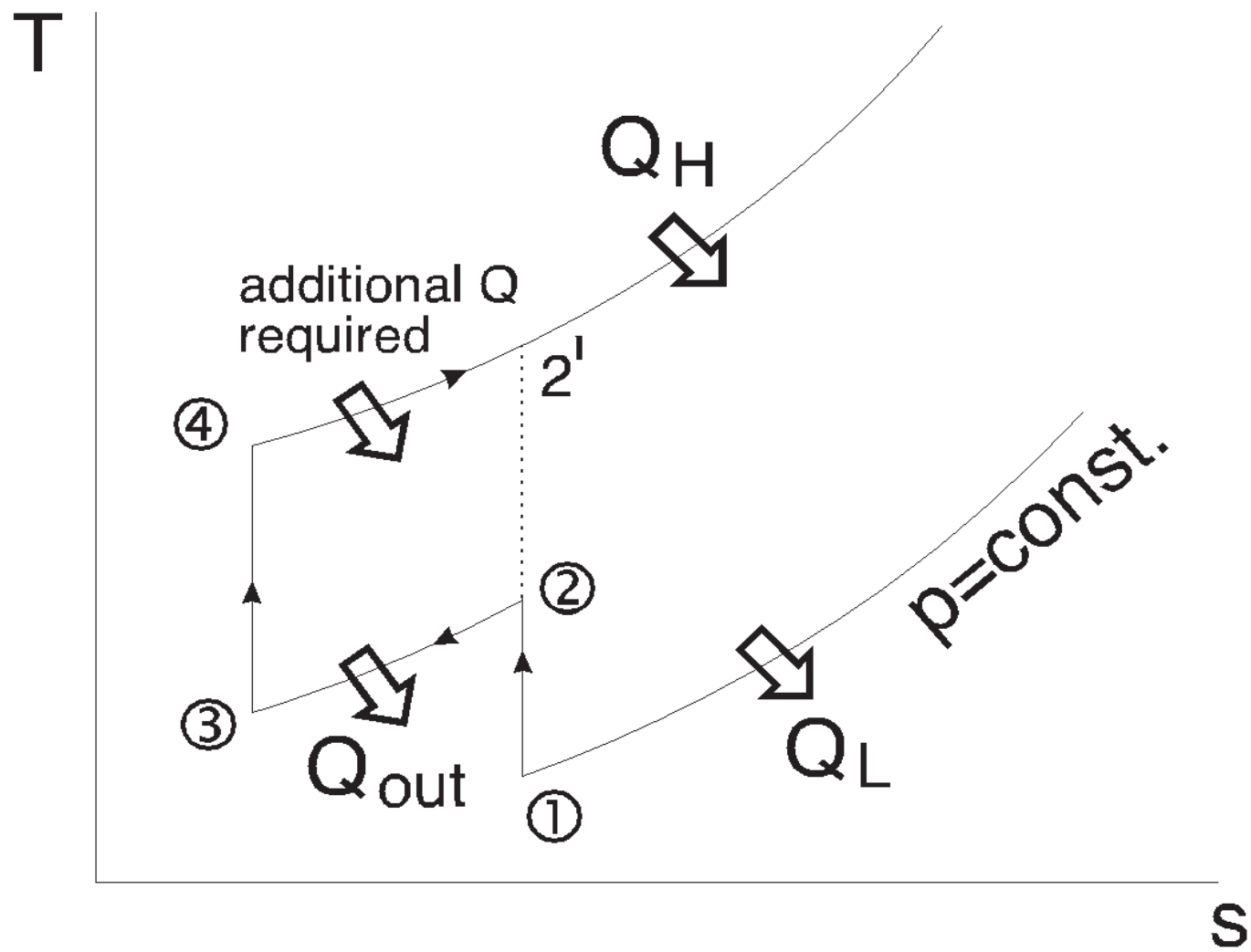
Brayton Cycle with Reheat



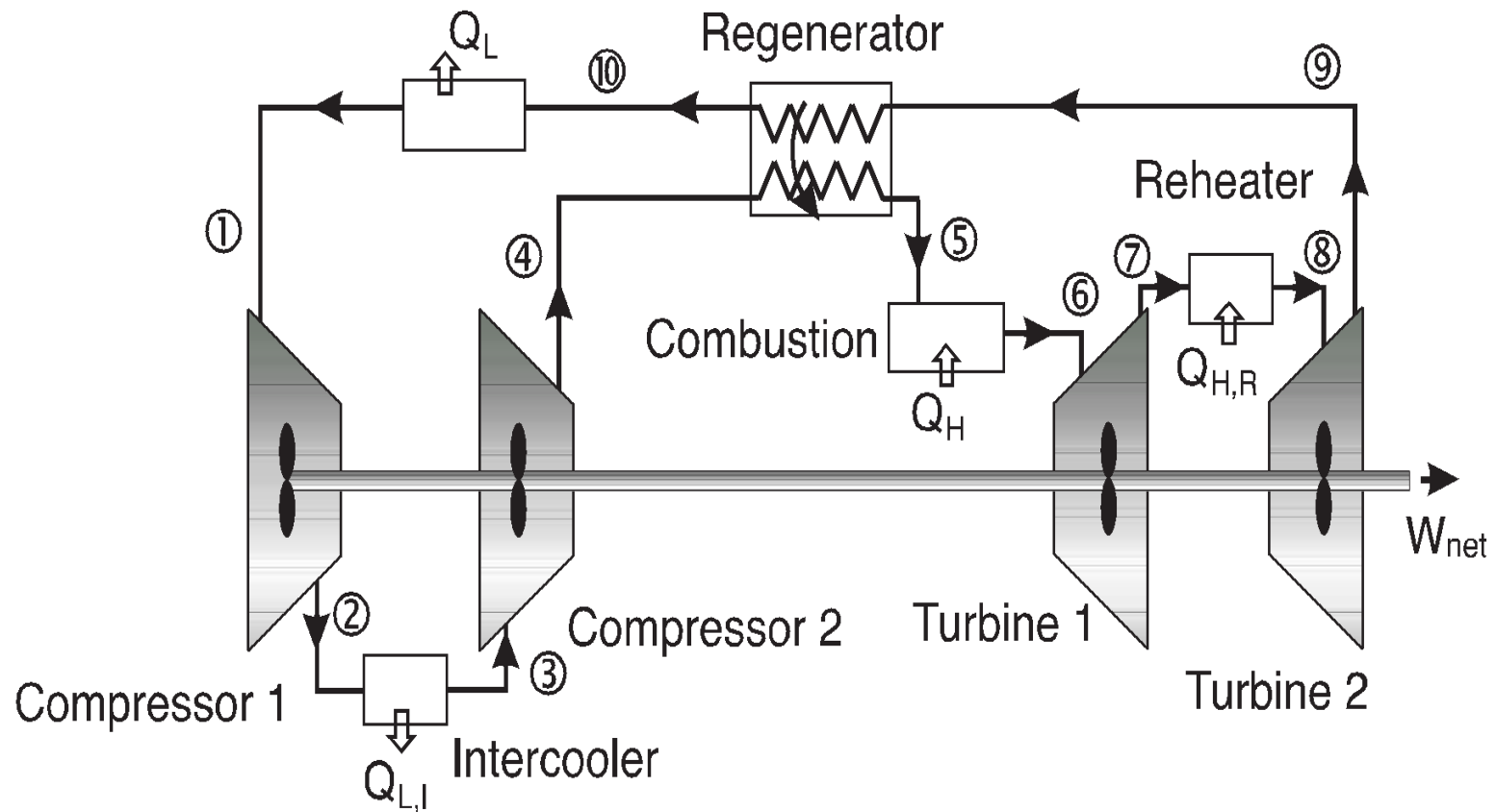


Compression with Intercooling





Brayton Cycle With Intercooling, Reheating and Regeneration



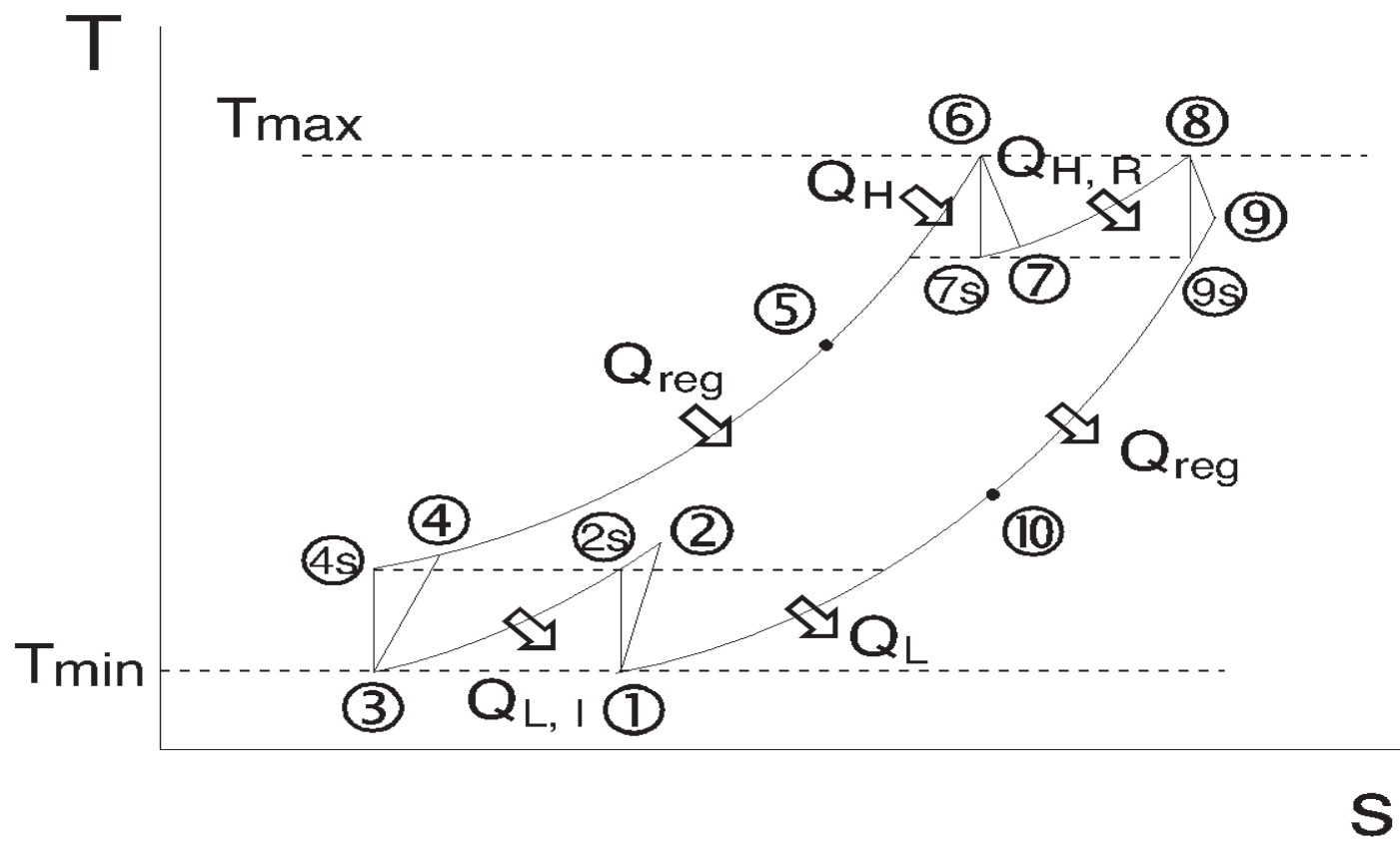
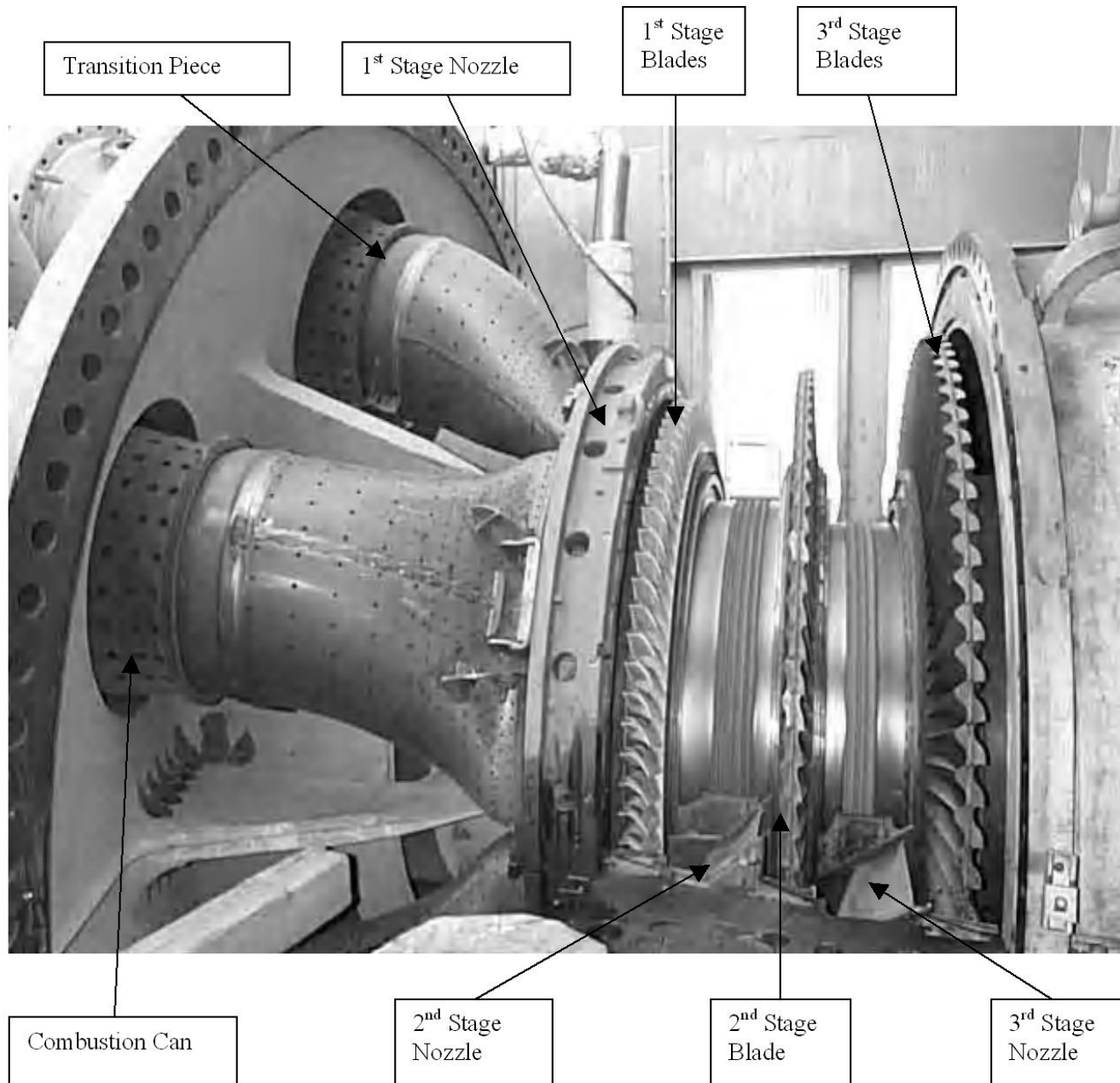


Figure 3 – An Axial-Flow Compressor



Figure 4 – A Combustion Chamber Can





Chapter 3

GAS TURBINE POWER PLANT

3.5 – IMPROVING SYSTEM PERFORMANCE

Improving system performance will be done by two methods :

I – improving system efficiency

II – improving system power

Although both methods seems to end up with similar goal, i.e improving system overall performance, but it is important to note that :

1 - improving system efficiency is by improving working fluid properties to do better job, and this is done by changing it's (P & T) for better thermodynamic behavior, while improving system power is by providing extra energy input to virtually raise energy output.

2 – improving efficiency by utilizing waste heat for further application , while improving power requires extra fuel which in fact decrease system efficiency.

3 – therefore , it is clear that the two methods have completely different approach, but aims towards common end results.

Methods to increase power

- The power output of a Brayton engine can be improved in the following manners:
- **Reheat**, wherein the working fluid—in most cases air—expands through a series of turbines, then is passed through a second combustion chamber before expanding to ambient pressure through a final set of turbines. This has the advantage of increasing the power output possible for a given compression ratio without exceeding any metallurgical constraints.(typically about 1000 °C)
- The use of an afterburner for jet aircraft engines can also be referred to as *reheat*, it is a different process in that the reheated air is expanded through a thrust nozzle rather than a turbine. The metallurgical constraints are somewhat alleviated enabling much higher reheat temperatures . (about 2000 °C)
- The use of reheat is most often used to improve the specific power (per throughput of air) and is usually associated with a reduction in efficiency, this is most pronounced with the use of afterburners due to the extreme amounts of extra fuel used .

Methods to improve efficiency

- The efficiency of a Brayton cycle can be improved in the following manners:

1 – Intercooling.

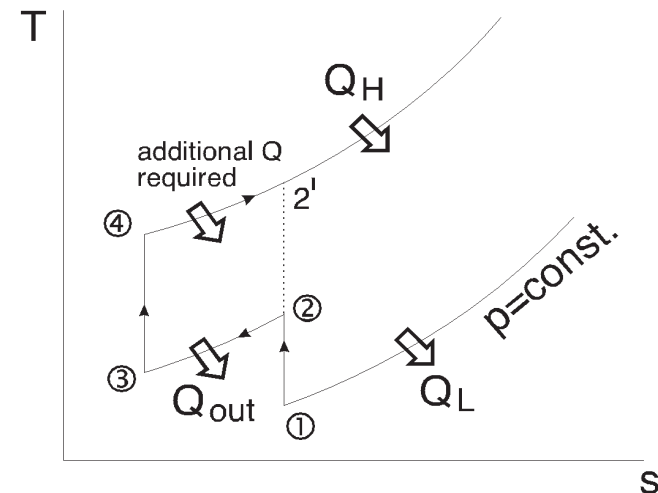
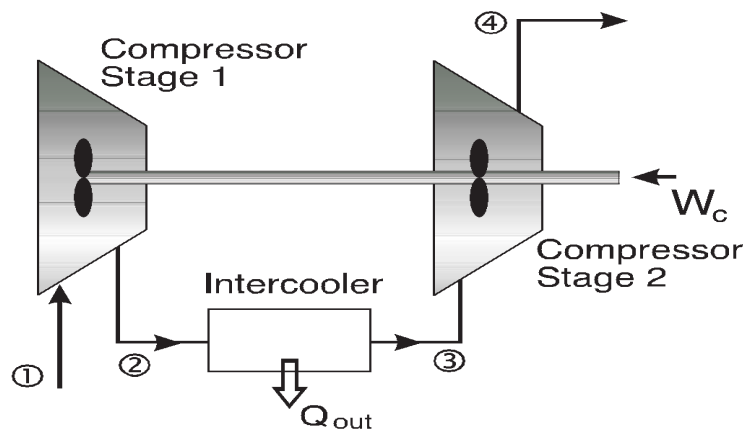
2 – Regeneration

3 – combined cycle.

4 - cogeneration

Intercooling

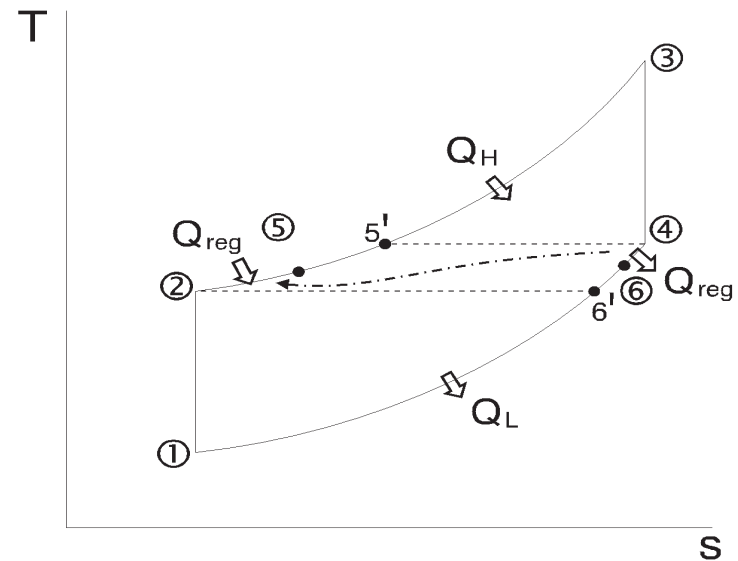
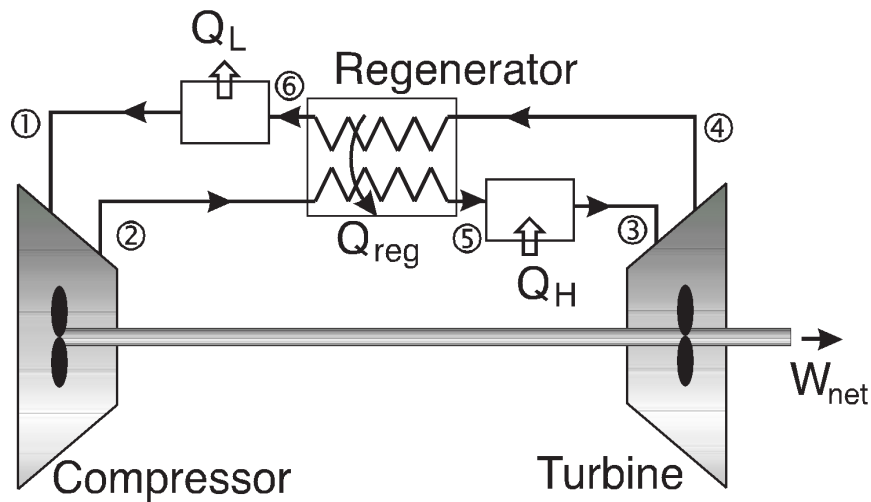
wherein the working fluid passes through a first stage of compressors, then a cooler, then a second stage of compressors before entering the combustion chamber. While this requires an increase in the fuel consumption of the combustion chamber, this allows for a reduction in the specific volume of the fluid entering the second stage of compressors, with an attendant decrease in the amount of work needed for the compression stage overall. There is also an increase in the maximum feasible pressure ratio due to reduced compressor discharge temperature for a given amount of compression, improving overall efficiency.



Regeneration

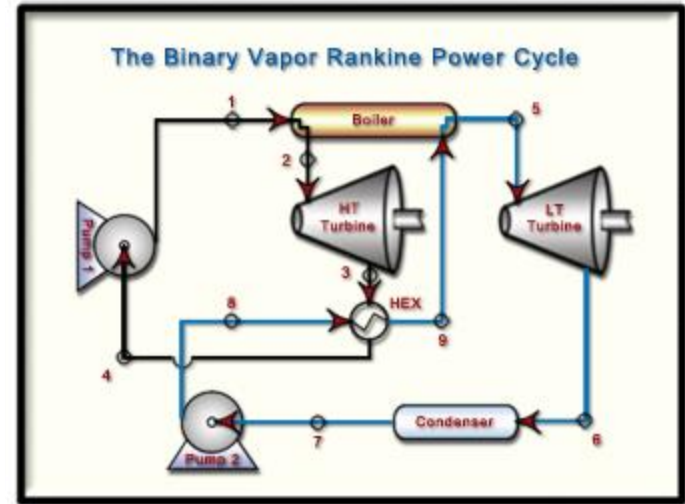
wherein the still-warm post-turbine fluid is passed through a heat exchanger to pre-heat the fluid just entering the combustion chamber. This directly offsets fuel consumption for the same operating conditions improving efficiency; it also results in less power lost as waste heat.

However, at higher pressure ratios, the compressor discharge temperature can exceed the exhaust temperature. Under these conditions, regeneration would be counterproductive. Therefore, regeneration is only an option when the pressure ratio is sufficiently low that the exhaust temperature is higher than the compressor discharge temperature.



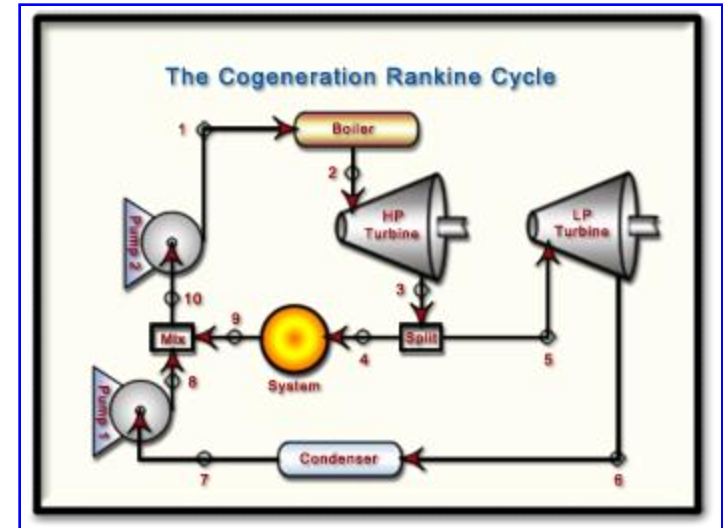
combined cycle

A Brayton cycle also forms half of the combined cycle system, which combines with a Rankine engine to further increase overall efficiency .



Cogeneration

Cogeneration systems make use of the waste heat from Brayton engines, typically for hot water production or space heating.



It is seen from previous lectures that the thermal efficiency is expressed as

$$\eta = 1 - \frac{1}{r_p^{(\gamma-1/\gamma)}}$$

$$\eta = f(r_p)$$

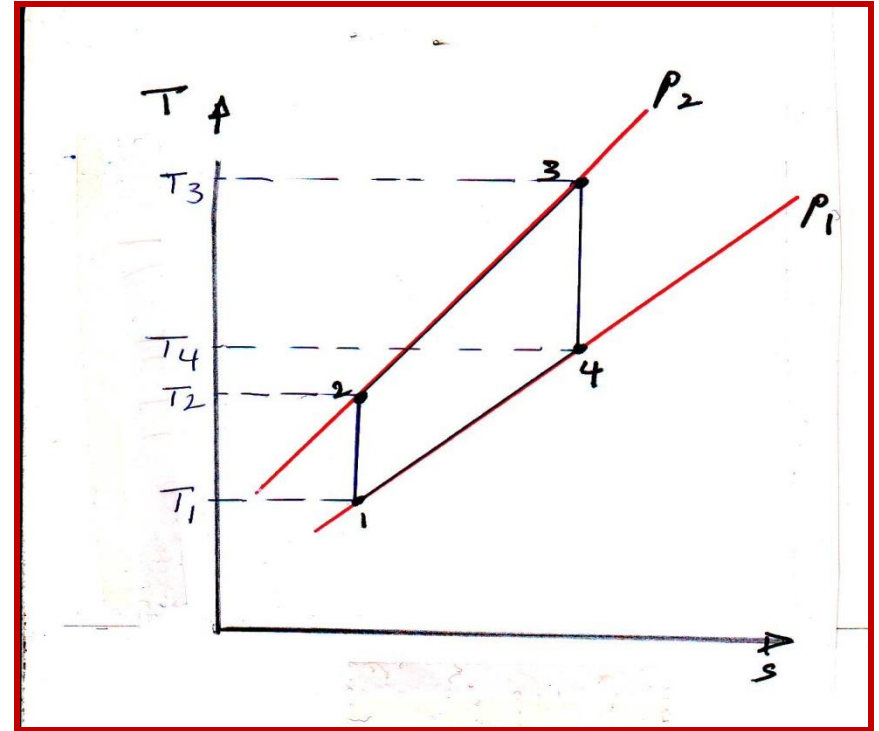
and the work ratio is

$$WR = 1 - \left[\left(\frac{T_1}{T_3} \right) \left(r_p^{\gamma-1/\gamma} \right) \right]$$

$$WR = f(r_p, T_1, T_3)$$

and the net work output is

$$NW = C_p \{ (T_3 - T_4) - (T_2 - T_1) \}$$



This shows that $W = f(T_1, T_3, r_p)$

However, for a given pressure ratio (r_p) and under specific initial conditions (P_1, T_1) the work output will be a function of (T_3)

$$W = f(T_3)$$

$$NW = C_p \{ (T_3 - T_4) - (T_2 - T_1) \}$$

$$NW = C_p \cdot T_1 \left[\left\{ \left(\frac{1}{T_1} \right) (T_3 - T_4) \right\} - \left\{ \left(\frac{1}{T_1} \right) (T_2 - T_1) \right\} \right]$$

$$NW = C_p \cdot T_1 \left[\left\{ \left(\frac{T_3}{T_1} \right) \left(1 - \frac{T_4}{T_3} \right) \right\} - \left\{ \left(\frac{T_2}{T_1} \right) - 1 \right\} \right]$$

$$NW = C_p \cdot T_1 \left[\left\{ \frac{T_3}{T_1} \left(1 - \frac{1}{r_p^{(\gamma-1/\gamma)}} \right) \right\} - \left\{ \left(r_p^{(\gamma-1/\gamma)} \right) - 1 \right\} \right]$$

If we assume that ($n = \frac{\gamma-1}{\gamma}$) and ($Z = r_p^n$) as we did previously, then (NW) will become

$$W = C_p \cdot T_1 \{ [(T_4 / T_1) (Z - 1) / (Z)] - (Z - 1) \}$$

$$W = C_p \cdot T_1 (Z - 1) \{ [(T_4 / T_1) / (Z)] - 1 \}$$

See regeneration section for review

Optimization

The temperature ratio (T_3/T_1) is actually represent the ratio of max to min cycle temperature under optimum operating conditions, i.e

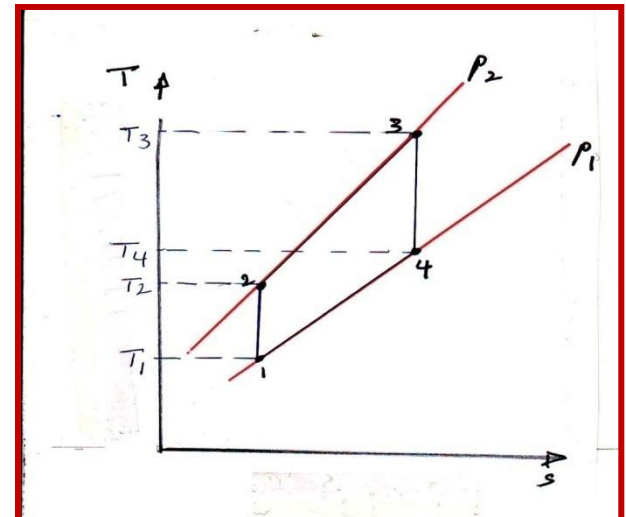
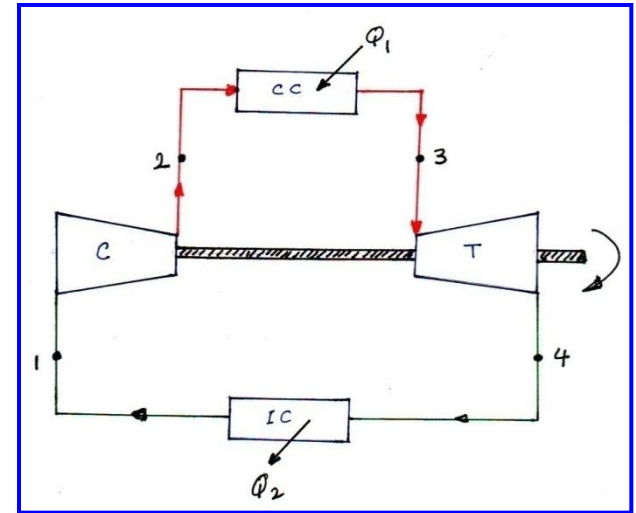
$$\frac{T_3}{T_1} \Rightarrow \text{for optimum consideration} \Rightarrow \frac{T_{max}}{T_{min}}$$

Analysis towards optimum state is conducted using mathematical approach of differentiating a specific function.

The function of such consideration is that of
[$NW = f(r_p)$], i.e

$$NW = C_p \cdot T_1 \left[\left\{ \frac{T_3}{T_1} \left(1 - \frac{1}{r_p^{(\gamma-1/\gamma)}} \right) \right\} - \left\{ (r_p^{(\gamma-1/\gamma)}) - 1 \right\} \right]$$

For max temperature ratio (T_3/T_1), the max output can be obtained by differentiation the above equation with respect to $(r_p^{(\gamma-1/\gamma)})$ and equating to zero, i.e



$$NW = C_p \cdot T_1 \left[\left\{ \frac{T_3}{T_1} \left(1 - \frac{1}{r_p^{(\gamma-1)/\gamma}} \right) \right\} - \left\{ (r_p^{(\gamma-1)/\gamma}) - 1 \right\} \right]$$

$$\frac{dW}{d(r_p^{(\gamma-1)/\gamma})} = C_p \cdot T_1 \left\{ \left(\frac{T_3}{T_1} \right) \left[\left(\frac{1}{r_p} \right)^{2(\gamma-1)/\gamma} \right] - 1 \right\} = 0$$

and since ($C_p \cdot T_1 \neq 0$), Therefore

$$\left\{ \left(\frac{T_3}{T_1} \right) \left[\left(\frac{1}{r_p} \right)^{2(\gamma-1)/\gamma} \right] - 1 \right\} = 0$$

$$\left\{ \left(\frac{T_3}{T_1} \right) \left[\left(\frac{1}{r_p} \right)^{2(\gamma-1)/\gamma} \right] \right\} = 1$$

$$\left\{ \left(\frac{T_3}{T_1} \right) = \left[(r_p)^{2(\gamma-1)/\gamma} \right] \right\}$$

$$\left\{ \left(\frac{T_3}{T_1} \right) = \left[(r_p)^{(\gamma-1)/\gamma} \right] \left[(r_p)^{(\gamma-1)/\gamma} \right] \right\}$$

rearrange to obtain

$$r_p = \left[\left(\frac{T_3}{T_1} \right)^{\frac{\gamma}{2(\gamma-1)}} \right]_{max}$$

from previous analysis, it's being shown that

$$\frac{T_2}{T_1} = r_p^n \Rightarrow \text{and} \Rightarrow \frac{T_3}{T_4} = r_p^n$$

Multiplying both equations to get:

$$r_p^n \cdot r_p^n = \frac{T_2}{T_1} \cdot \frac{T_3}{T_4} = \left(\frac{T_3}{T_1} \right)_{max}$$

since

$$r_p^n \cdot r_p^n = r_p^{2n}$$

$$r_p^{2n} = [r_p]^{2n} = [r_p]^{\frac{2(\gamma-1)}{\gamma}}$$

$$\text{also } r_p = \left(\frac{T_3}{T_1} \right)^{\frac{\gamma}{2(\gamma-1)}}$$

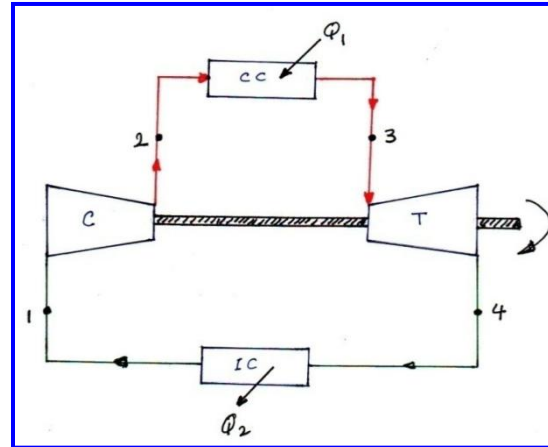
$$\text{Therefore } [r_p]^{\frac{2(\gamma-1)}{\gamma}} = \left[\left(\frac{T_3}{T_1} \right)^{\frac{\gamma}{2(\gamma-1)}} \right]^{\frac{2(\gamma-1)}{\gamma}} \Rightarrow \Rightarrow \Rightarrow \Rightarrow \Rightarrow [r_p]^{\frac{2(\gamma-1)}{\gamma}} = \frac{T_3}{T_1}$$

Again, it's previously shown that

$$\frac{T_2}{T_1} = r_p^n \Rightarrow \text{and} \Rightarrow \frac{T_3}{T_4} = r_p^n$$

$$r_p^n = \frac{T_2}{T_1} = \frac{T_3}{T_4}$$

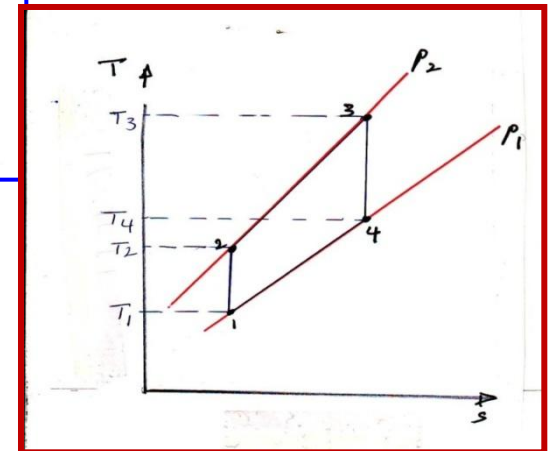
$$[r_p]^{\frac{2(\gamma-1)}{\gamma}} = \frac{T_3}{T_1}$$



therefore

$$[r_p]^{2n} = \frac{T_3}{T_1} = \frac{T_2}{T_1} \cdot \frac{T_3}{T_4} \Rightarrow \Rightarrow \frac{T_3}{T_1} = \frac{T_2}{T_1} \cdot \frac{T_3}{T_4}$$

$$\frac{T_2}{T_4} = 1 \Rightarrow \Rightarrow T_2 = T_4$$



This means that

DISCUSSION

See the schematic & T-s diagrams, and explain what ($T_2 = T_4$) means

Returning to $[r_p]^{\frac{2(\gamma-1)}{\gamma}} = \frac{T_3}{T_1}$

$$r_p = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}} \Rightarrow \Rightarrow \Rightarrow \Rightarrow \quad (r_p)^{\frac{\gamma-1}{\gamma}} = \left(\frac{T_3}{T_1}\right)^{1/2}$$

sub in previous eq. $NW = C_p \cdot T_1 \left[\left\{ \frac{T_3}{T_1} \left(1 - \frac{1}{r_p^{(\gamma-1/\gamma)}} \right) \right\} - \left\{ (r_p^{(\gamma-1/\gamma)}) - 1 \right\} \right]$

to obtain

$$W = C_p \cdot T_1 \left[\left(\frac{T_3}{T_1} \right) - 2 \left(\frac{T_3}{T_1} \right)^{1/2} + 1 \right]$$

This eq. in square brackets is similar to an algebraic equation of this form

$$X^2 - 2X + 1 = (X - 1)^2$$

Therefore

$$X^2 - 2X + 1 = (X - 1)^2$$

$$\left[\left(\frac{T_3}{T_1} \right) - 2 \left(\frac{T_3}{T_1} \right)^{1/2} + 1 \right] = \left(\left\{ \frac{T_3}{T_1} \right\}^{1/2} - 1 \right)^2$$

From these results , the followings should be noted :

I - [(T3/T1) must be > 1] in order to have maximum power output .

II - from eq. shown below

$$\left\{ \left(\frac{T_3}{T_1} \right)_{max} = (r_p)^{2(\gamma-1)/\gamma} = \left[(r_p)^{(\gamma-1)/\gamma} \right] \cdot \left[(r_p)^{(\gamma-1)/\gamma} \right] \right\}$$

This max temperature ratio [(T3/T1)]_{max} fixes the value of (r_p) as

$$r_p = \left(\frac{T_3}{T_1} \right)^{\frac{\gamma}{2(\gamma-1)}}$$

And so ,

$$r_p \text{ must be } \leq \left(\frac{T_3}{T_1} \right)^{\frac{\gamma}{2(\gamma-1)}}$$

III - also from previous eq. shown below

$$(P_2 / P_1) = r_p$$

This means that in order for a compression process to take place in the compressor, the pressure after compression must exceed that before compression, so

$$(P_2 / P_1) = r_p \text{ must be } \geq 1$$

IV – it can be concluded from (I – III) above

$$(T_3/T_1) > 1$$

$$r_p \text{ must be } \geq 1$$

$$\left(\frac{T_3}{T_1} \right)^{\frac{\gamma}{2(\gamma-1)}} \geq r_p \geq 1$$

conclusion

- From all of the above analysis, and from practical point of view, it has been shown that always the temperature of exhaust gas from turbine is higher than that of air after compressor, i.e
- $T_4 > T_2$
- This would mean that the heat energy in the exhaust gas can be utilized to increase the temperature of the compressed air before entering the combustion chamber, and therefore would improve combustion economy and combustion efficiency, and would as an overall results improves the system efficiency.

Comparison assessment

Gas turbine power plant is shown to have means of *performance improvement* both in terms of power and/or efficiency.

Also, it has being shown that optimum state can be achieved if specific requirement is fulfilled. This also was shown to be conflicted when power & efficiency are considered at the same time.

cycle	Ideal efficiency	Actual efficiency	Net Work output	Work ratio	Power output
Standard					
Reheat					
Regeneration					
Reheat + regeneration					
Inter-cooling					

cycle	Ideal efficiency	Actual efficiency	Net Work output	Work ratio	Power output
Standard	$\eta = 1 - \frac{1}{r_p^n}$	$\eta_{th} = \frac{(T_3 - T_1) - C_p (T_2 - T_4)}{C_p (T_3 - T_2)}$			
Reheat					
Regeneration					
Reheat + regeneration					
Inter-cooling					

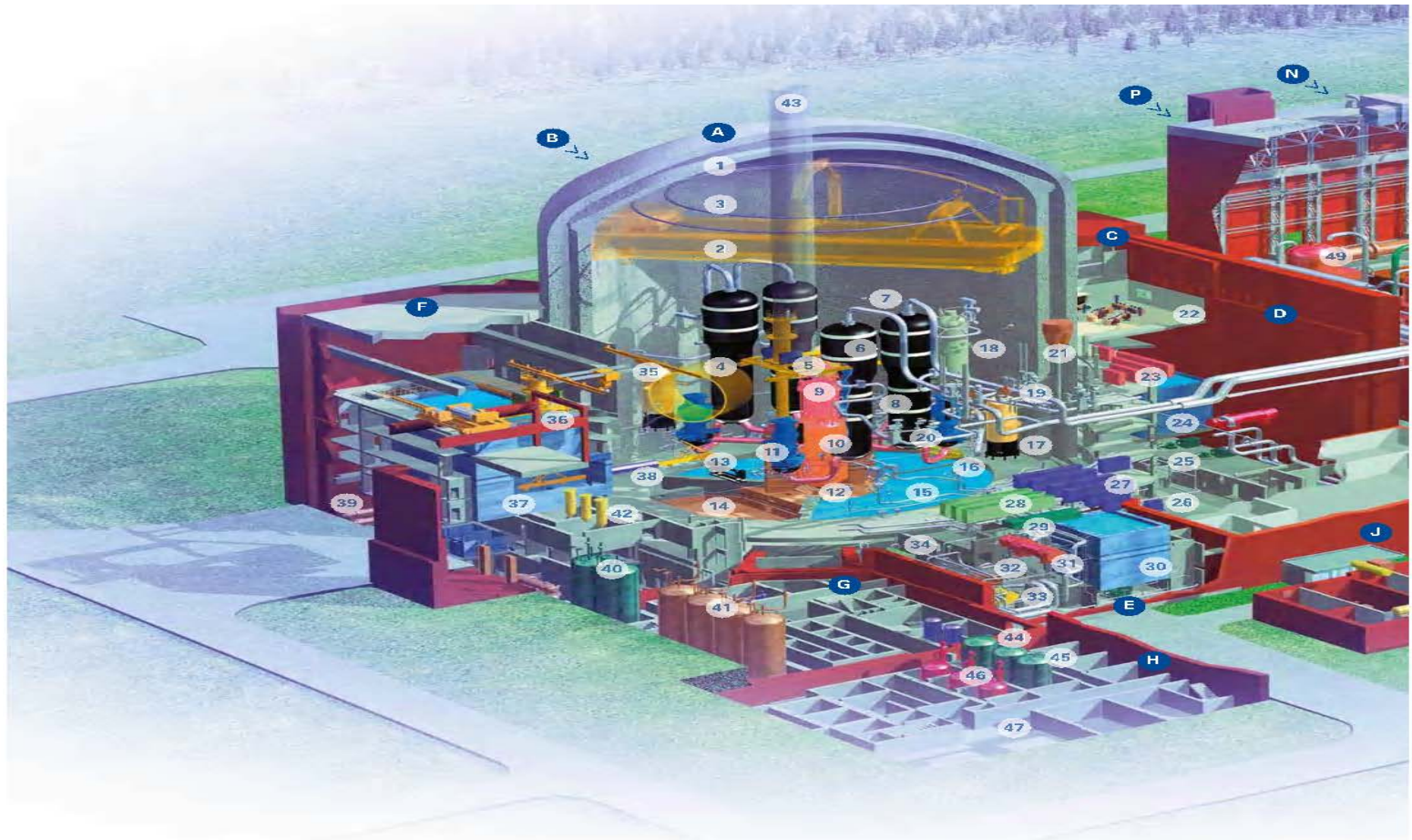
cycle	Ideal efficien cy	Actual efficien cy	Net Work output	Work ratio	Power output
Standard			$NW = C_p [(T_3 - T_4) - (T_2 - T_1)]$	$WR = 1 - [(T_1 / T_3) r_p^n]$	
Reheat					
Regeneration					
Reheat + regeneration					
Inter-cooling					

cycle	Ideal efficien cy	Actual efficienc y	Net Work output	Work ratio	Power output
Standard					
Reheat					
Regeneration					
Reheat + regeneration					
Inter-cooling					

Chapter Five

Nuclear Power Plant

5.01 - Introduction



A Reactor building

- 1 Inner and outer containment building
- 2 Reactor building main crane (polar crane)
- 3 Containment heat removal system: sprinklers
- 4 Equipment hatch (large components)
- 5 Refuelling machine
- 6 Steam generator
- 7 Main steam lines
- 8 Main feedwater lines
- 9 Reactor control rod drives
- 10 Reactor pressure vessel
- 11 Reactor circuit reactor coolant pump
- 12 Primary circuit main coolant lines

- 13 Primary circuit volume control system heat exchangers
 - 14 Core melt spreading area
 - 15 Emergency cooling water storage (in-containment refuelling water storage tank, IAWST)
 - 16 Intake screens for the cooling system for reactor emergency cooling and containment heat removal system
 - 17 Hydraulic accumulator of the reactor emergency cooling system
 - 18 Primary circuit pressurizer
 - 19 Main steam valves
 - 20 Feedwater valves
 - 21 Main steam system safety valve and relief valve exhaust silencer
- B Safeguard building division 1**

C Safeguard building division 2

- 22 Main control room
 - 23 Computer room
 - 24 Emergency feedwater tank
- D Safeguard building division 3**
- 25 Emergency feedwater pump
 - 26 Medium head safety injection pump
- E Safeguard building division 4**
- 27 Switchgear room
 - 28 Instrumentation & control room
 - 29 Battery rooms
 - 30 Emergency feedwater tank
 - 31 Component cooling system heat exchanger
 - 32 Low head safety injection pump
 - 33 Containment heat removal system heat exchanger (sea water circuit)

- 34 Containment heat removal system heat exchanger

F Fuel building

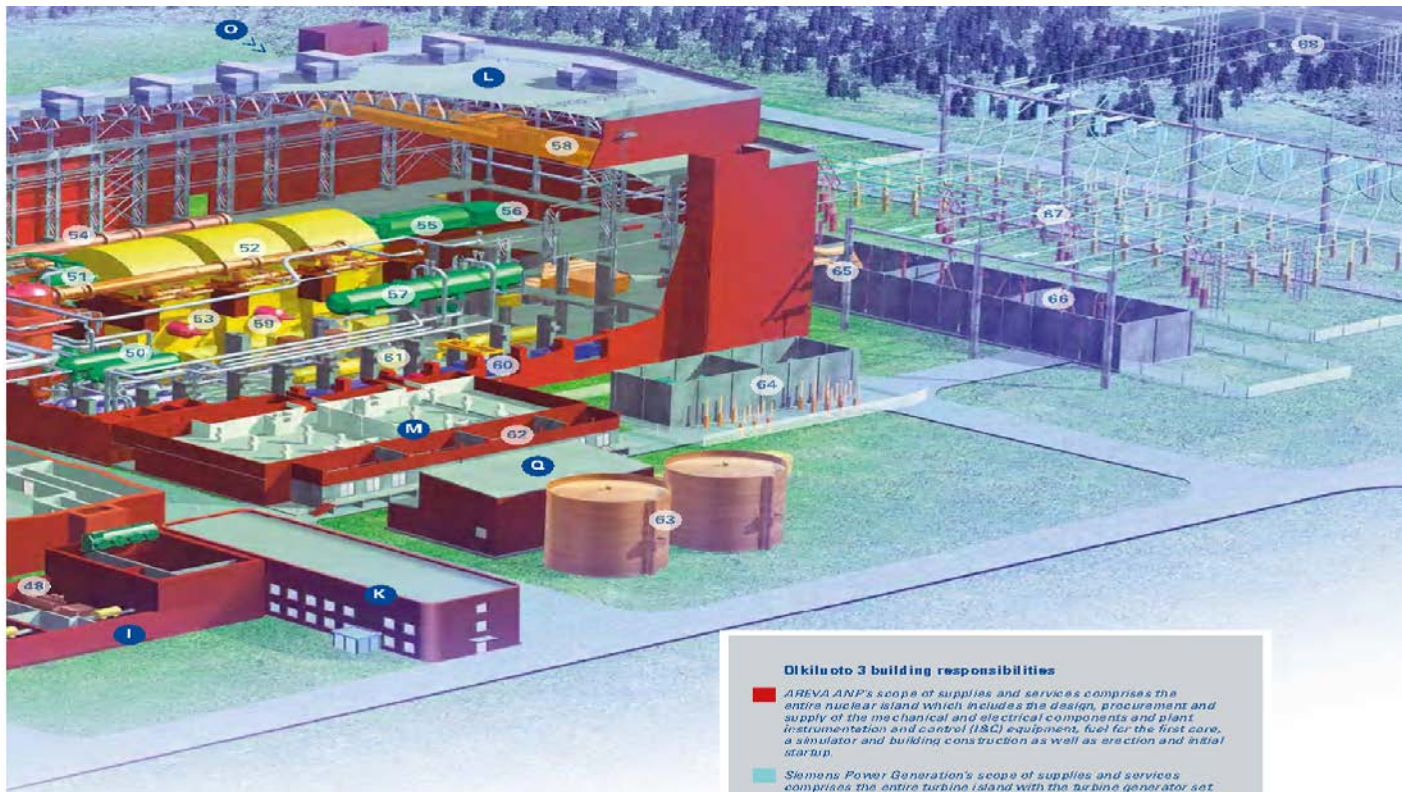
- 35 Fuel building crane
- 36 Refuelling machine
- 37 Fuel pools
- 38 Fuel transfer tube
- 39 Fuel pool cooling system heat exchanger

G Reactor plant auxiliary building

- 40 Coolant supply and storage system
- 41 Coolant supply and storage system
- 42 Offgas delayer
- 43 Ventilation stack

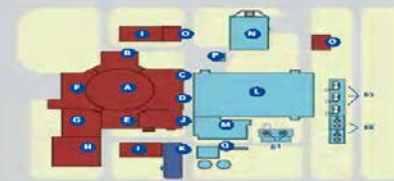
H Radioactive waste processing building

- 44 Liquid waste collecting tank
- 45 Monitoring tanks



Olkiluoto 3 building responsibilities

- AREVA ANP's scope of supplies and services comprises the entire nuclear island which includes the design, procurement and supply of the mechanical and electrical components and plant instrumentation and control (I&C) equipment, fuel for the first core, a simulator and building construction as well as erection and initial start-up.
- Siemens Power Generation's scope of supplies and services comprises the entire turbine island with the turbine generator set. This includes design, procurement and supply of the electrical and mechanical components, the turbine I&C equipment and building construction as well as erection and initial start-up.
- TVO as owner is responsible for the licensing process and is responsible for site infrastructure and excavation, grid connection and some auxiliary buildings.



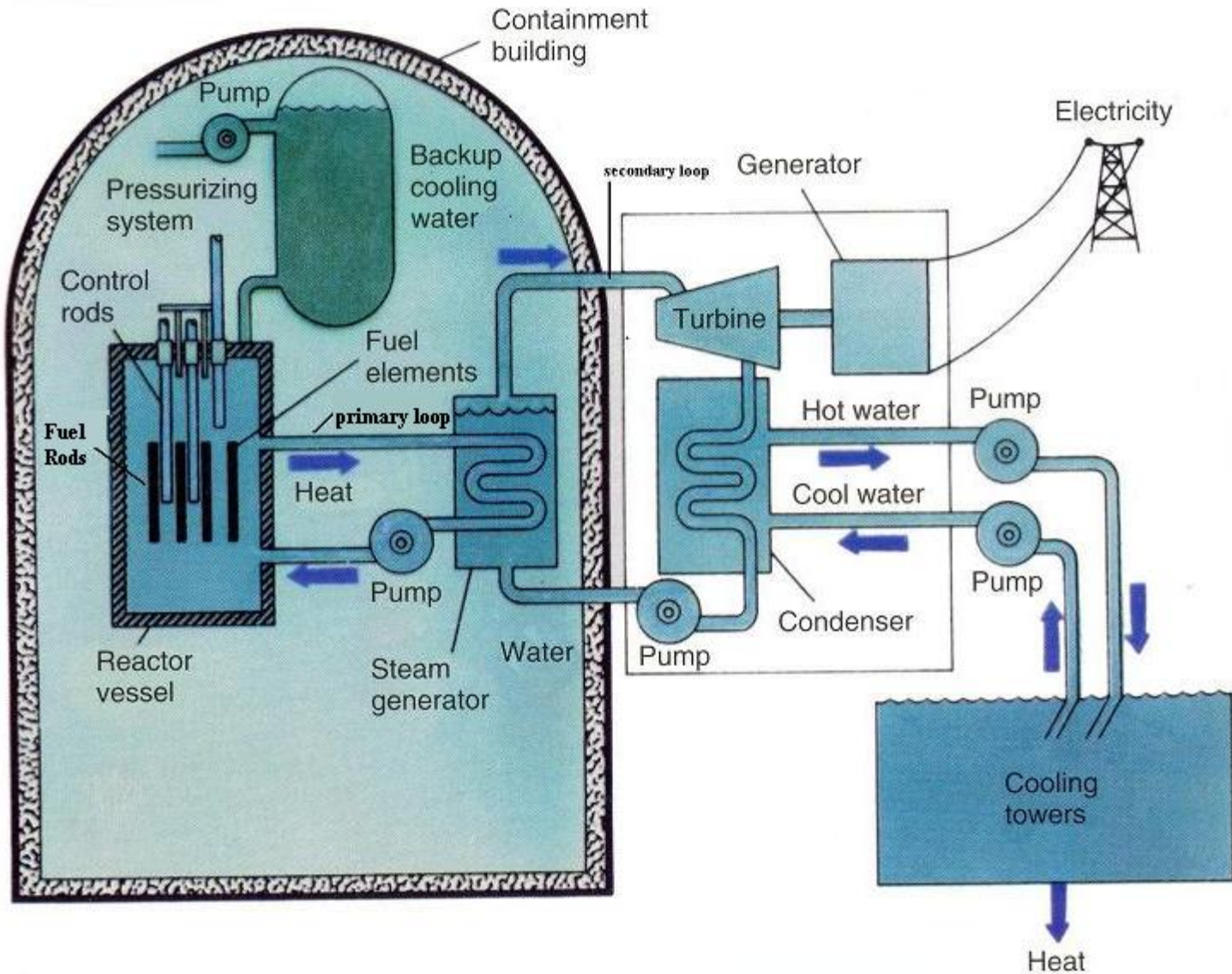
- | | |
|--|--|
| 46 Concentrate tanks | 58 Turbine building main crane |
| 47 Drum storage area | 59 Low-pressure feedwater preheater |
| I Emergency power generating building | 60 Feedwater pumps |
| 48 Emergency diesel generators | 61 Low-pressure feedwater preheater |
| J Access building | M Switchgear building |
| K Office building | 62 Transformer boxes |
| L Turbine building | N Circulating water pump building |
| 49 Moisture separator/reheater | O Essential service water pump building |
| 50 High-pressure feedwater preheaters | P Anti-icing pumps |
| 51 High-pressure turbine | Q Auxiliary boiler building |
| 52 Low-pressure turbine | 63 Demineralized water storage tanks |
| 53 Condensers | 64 Auxiliary stand-by transformer |
| 54 Cross over lines | 65 Unit transformers |
| 55 Generator | 66 Auxiliary normal transformers |
| 56 Exciter | 67 Switchyard |
| 57 Feedwater tank | 68 High-voltage lines |

Computer graphics: Ansgar B. Peters

- 1 Moisture separator reheater (MSR)
- 2 High-pressure turbine
- 3 Low-pressure turbine
- 4 Condenser
- 5 Generator



Schematic of a Nuclear Power Plant



Introduction

Nuclear power, although controversial, produces approximately 17% of the world's electricity. There are over 400 nuclear power plants throughout the world. Of those, about 100 are in the USA. Many countries depend on nuclear power for their electricity supply, some more than others. For example; France is reputed to generate approximately 75% of its requirements from nuclear plants and the USA about 15%.

The use of nuclear power plant is a strategic and economic necessity for the world to maintain future power production :

1. **Strategic reasons**
due to oil reserve will be totally consumed in time, an alternative and efficient source of power must be established.
2. **Economic reasons**
one large nuclear PP saves as much as of (50000) barrels of oil per day, assuming the cost of (\$50/barrel), thus resulting in a saving of (\$2,500,000) for one PP for one day. Accordingly, such PP would retain it's capital cost within few years.

Advantages

1. Unit cost per kW.hr is lower than that for coal
2. Improving the conventional PP efficiency
3. The by-products are useful:

special case:

a PP may have it's main purpose to produce **plutonium** and the by-products is used in power generation plant

disadvantages

1. Problem of nuclear safety of waste disposal.
2. Weapons production of mass destruction.
3. Economic reasons
4. Public opinion and uncertain safety.
5. Nuclear fuel security.

Chapter Five

Nuclear Power Plant

5.02 – Nuclear Chemistry

Basic Chemistry

- The atom is the basic unit of the nuclear reaction, and the size of it, is such a small, that (10^{13}) atoms occupies a volume of less than the pin head. However each atom is itself like a miniature universe.
- The atom is normally electrically neutral, where almost the entire of it's mass is concentrated in the **nucleus**, whereas it's volume is determined by envelope enclosing the outer orbit, such volume is mostly an empty space.
- Energy from any chemical reaction is developed by the fact that when an **electrons** changes from one orbit to another, energy is either emitted or absorbed.
- **The nuclear reaction is concerned with the nucleus and not the electron orbiting behavior**, where the nucleus has a very high cohesive force binding the **protons and neutrons**. This force is much higher and stronger than that holding the electrons in orbit.
- Such nuclear reaction is splitting the nucleus (fission) and is accompanied by the release of a very large amount of energy.

Atom structure

- In general the atom structure can be described as :
 - 1- the atom of an element is made up of three sub-atomic units:
 - a- electrons (-ve charge)
 - b- protons (+ve charge)
 - c- neutrons (no charge)
- the electrical charge is equal in magnitude opposite in polarity.
- 2- the atom consists of :
- i- nucleus at the centre.
 - ii- a system of electrons in motion outside the nucleus.
- 3- the mass of the atom is almost entirely concentrated in the nucleus
 - 4- the volume of the atom is the volume which contains all of the moving electrons.
 - 5- nucleus at the center consists of the (+ve) charge particles (protons) and the charge-less (neutron). At this nucleus, most of the mass of the atom is concentrated.
 - 6- the electrons are of a very small mass relative to the protons (about 1/1800), and travels at a very high velocity around the nucleus in a specific orbit or shells.
 - 7- the atom as a whole is electrically neutral, where
 - number of protons (+ve) = number of electrons (-ve) in orbit

Chemical symbols

- Symbols that represent nuclear chemistry is shown below :



z : number of protons (atomic number)

n : number of nucleons (mass number)

X : the usual chemical symbols

- Z : the atomic number defines the number of protons in the nucleus , which is the same number as the orbital electrons.
- n : represent the total number of nucleons in the nucleus, which is the sum of
- (number of protons + number of neutrons)

Examples - 1

- ${}^1_1\text{H}^1$: hydrogen
- ${}^2_1\text{H}^2$: deuterium (${}^2_1\text{D}^2$)
- ${}^4_2\text{He}^4$: helium
- ${}^{234}_{92}\text{U}$: uranium 234
- ${}^{235}_{92}\text{U}$: uranium 235
- ${}^{238}_{92}\text{U}$: uranium 238
- ${}^{239}_{94}\text{Pu}$: plutonium

Examples - 2

- Calculation of number of neutrons y :
number of neutrons = mass number – atomic number
(protons)

$$y = n - z$$

- For example

92U234 : uranium 234

$$y = 234 - 92 = 142$$

92U235 : uranium 235

$$y = 235 - 92 = 143$$

Atom description

- *Mass of atom particles :*

neutron mass = 1.008665 amu

proton mass = 1.007277 amu

electron mass = 0.0005486 amu

where amu is atomis mass unit (e), and $\text{amu} = (1.66 \times 10^{-27}) \text{ kg}$

from which it can be seen that most of the weight of the atom is concentrated in the nucleus.

- *Volume of atom particles :*

radius of the nusleus = 10^{-16} m

radius of the atom = 10^{-11} m

- *Atom behavior :*

* the atom is electrically neutral, i.e ,the numbers of electron (-ve) and the numbers protons (+ve) are equal

* No. of electrons (orbital), determine the atom chemical family and behavior

* No. of protons & neutrons, establish the nuclear characteristics of the atom

Useful terms

1. **Fission**
2. **Fertelization**
3. **Isotopes**
4. **Heavy water**
5. **Radioactivity**
6. **Fusion**

1 - Fission

simply, fission is the action of splitting the nucleus, or specifically

“The spontaneous disintegration of a heavy atom into two or more lighter one, whereby the process involves a loss of mass which is converted into nuclear energy”

2 – Fertelization

- This is the union of two different particles (U238 + neutron) to form a new products (Pu239), for example :
- U238 capture a neutron, becomes radioactive and decay to Pu239 which itself is radioactive. striking Pu239 by a neutron produces Pu240 which is fertile. Further neutron strike produces fissionable Pu241

3 - Isotopes

Isotopes can be defined as :

“the atomic forms of an element differ in atomic mass but not in chemical properties”.

Or

“when atoms of an element have same number of protons but a different number of neutrons”

Ex. ${}^{92}_{\text{U}}234$: uranium 234
 ${}^{92}_{\text{U}}235$: uranium 235

Where isotopes has :

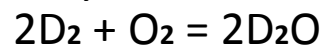
1. Same atomic number
2. Same proton number in nucleus
3. And therefore, the differences in mass number between isotopes of a given element are accounted for by the variation in the number of neutrons in the nucleus.

4 - Heavy water

ordinary water uses ordinary hydrogen:



Heavy water uses hydrogen (H_2) isotopes “deuterium (D_2)”:



Therefore the chemical symbols are

ordinary water is (H_2O)

heavy water is (D_2O)

5 - Radioactivity

- * radioactive element continuously undergoes spontaneous (without outside help) disintegration
- * such disintegration usually occurs with the emission of one or more smaller particles from parent nucleus and thus changing it into another, or daughter nucleus
- * parent nucleus $\rightarrow$ decay to $\rightarrow$ daughter nucleus
- * the daughter nucleus may or may not be stable

6- Fusion

- Two light nuclear particles combine or “fuse” together by which energy is released.
- The product nuclei have less mass than the original particles.
- The mass difference is converted to energy at a rate governed by Einstein equation:

$$E = \Delta m \cdot c^2$$

Chapter Five

Nuclear Power Plant

5.03 – Process of energy release

Methods of energy release

- **Fission**
- is a [nuclear reaction](#) in which the [nucleus](#) of an atom splits into smaller parts, often producing free [neutrons](#) and lighter [nuclei](#), which may eventually produce [photons](#) (in the form of [gamma rays](#)).
- Fission of heavy elements is an [exothermic reaction](#) which can release large amounts of [energy](#) both as [electromagnetic radiation](#) and as [kinetic energy](#) of the fragments ([heating](#) the bulk material where fission takes place).
- Nuclear fission produces:
 1. energy for [nuclear power](#) and to
 2. drive the explosion of [nuclear weapons](#).
- Both uses are made possible because certain substances called [nuclear fuels](#) undergo fission when struck by free neutrons and in turn generate neutrons when they break apart. This makes possible a self-sustaining [chain reaction](#) that releases energy:
 1. at a controlled rate in a [nuclear reactor](#)
 2. at a very rapid uncontrolled rate in a [nuclear weapon](#)

Fusion

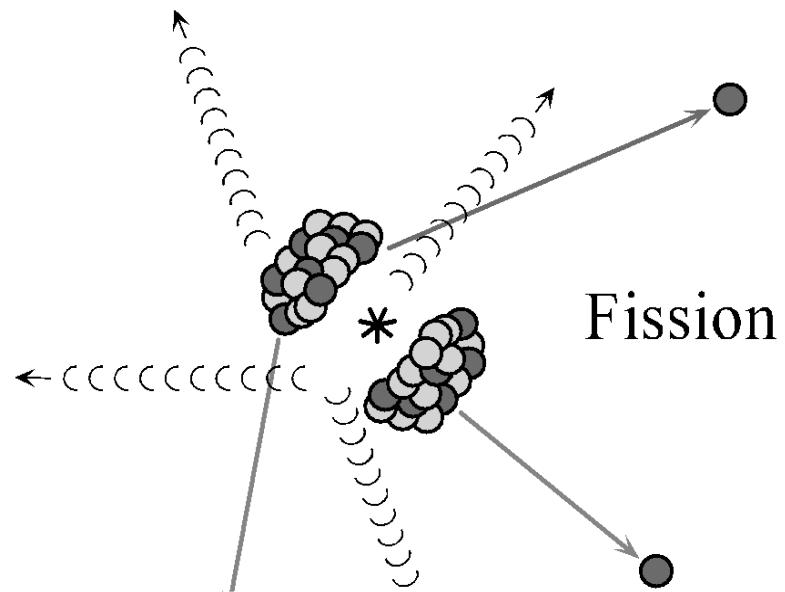
It takes considerable energy to force nuclei to fuse, even those of the lightest element, [hydrogen](#). This is because all nuclei have a positive charge (due to their protons), and as like charges repel, nuclei strongly resist being put too close together. Accelerated to high speeds (that is, heated to thermonuclear temperatures), they can overcome this electromagnetic repulsion and get close enough for the attractive [nuclear force](#) to be sufficiently strong to achieve fusion. The fusion of lighter nuclei, which creates a heavier nucleus and a [free neutron](#), generally releases more energy than it takes to force the nuclei together; this is an [exothermic process](#) that can produce self-sustaining reactions.

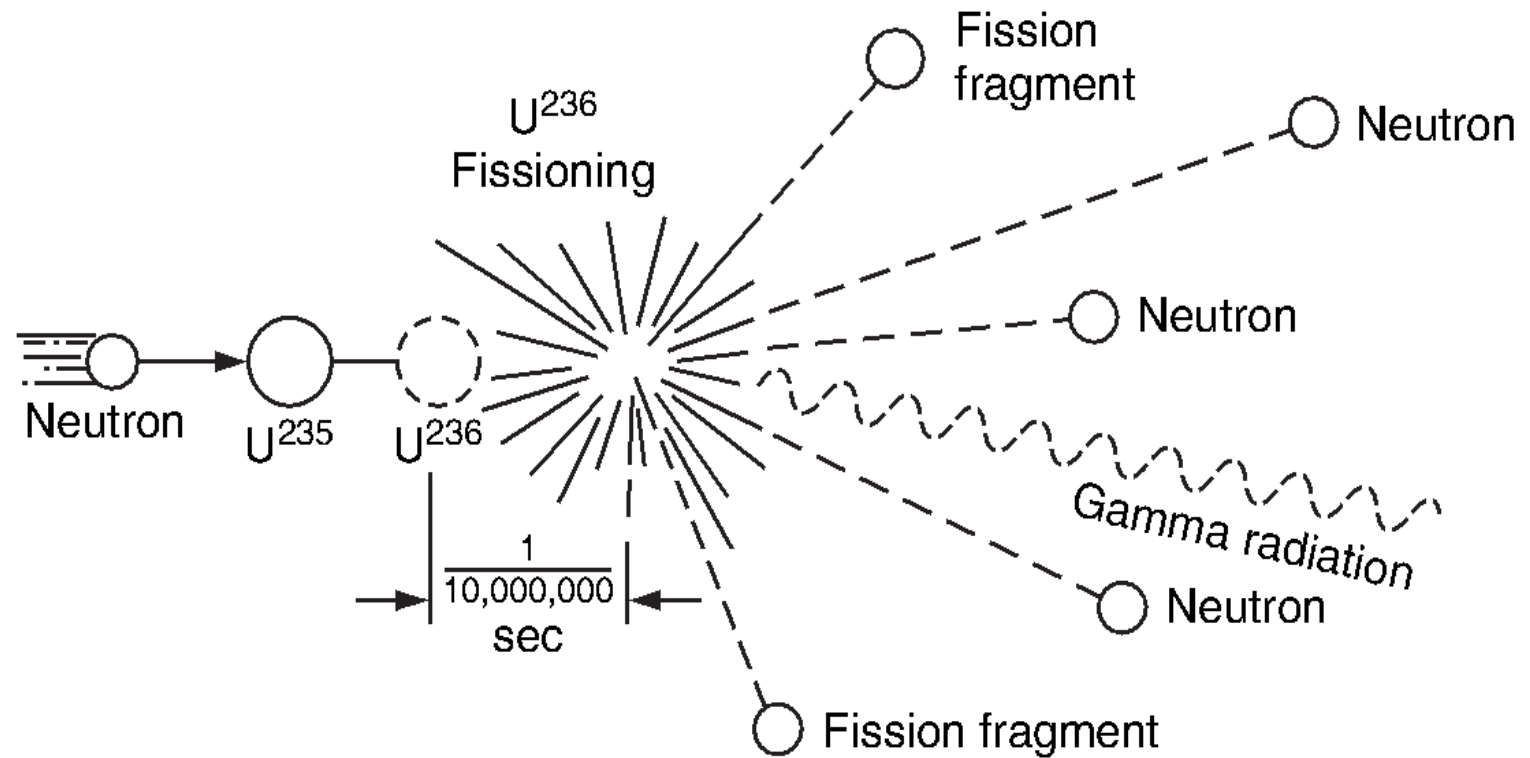
Fission Process

- This process produces :
 1. 200 MeV of energy
 2. 2-3 neutrons
 3. 2 lighter nuclei (fission fragments)
 4. Gama ray
 5. Neutrinos

The fission fragments undergo radioactive decay, thus producing additional fission products.

Fig.1



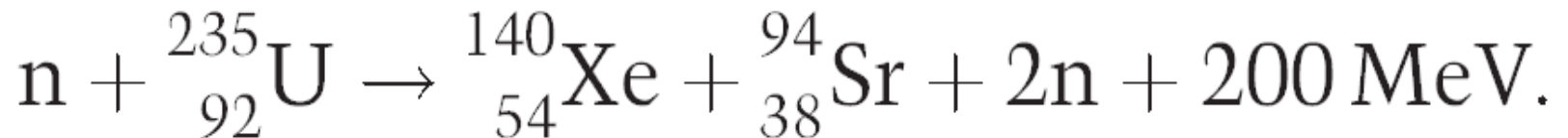


Fissile & Fertile

- Natural uranium is composed of
 - *99.3 % isotope (U238) non-fissionable,
 - *0.7 % uranium (U235) fissionable
- There are two classes of fissionable materials :
 1. **Fissile material**; is the one that will undergo fission when bombarded (strike) by neutrons of any energy. ex. U235
 2. **Fertile material**; is the one that will capture a neutron and thus transmute by radioactive decay into a fissile material. Ex U238

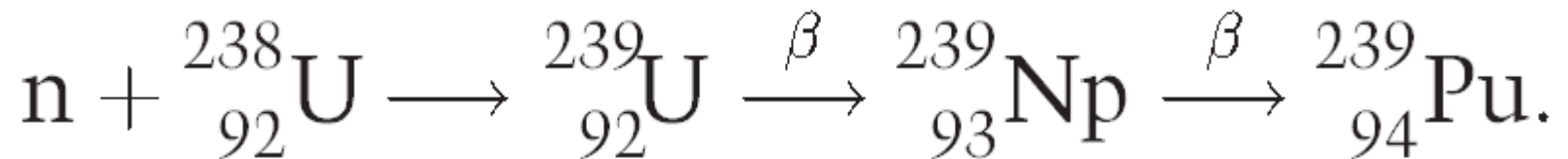
Fissile U235

- This is a naturally fissionable material, which requires a simple detonation element (neutron) to initiate fission reaction as shown below :

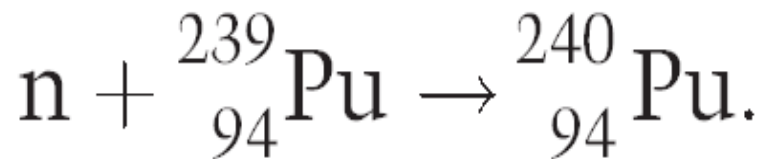


Fertile U238

U238 capture a neutron, becomes radioactive and decay to Pu239 which itself is radioactive. striking Pu239 by a neutron produces Pu240 which is fertile. Further neutron strike produces fissionable Pu241



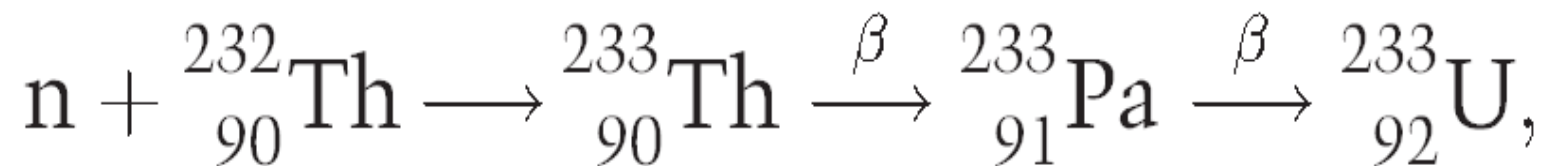
Plutonium Pu



- Plutonium-240, however, is again a fertile material. If it capture a second neutron, it will become:
- Plutonium-241
- Which is fissile material

Thorium Th232

- Th232 capture a neutron, undergoes decay as shown below, yielding the fissile U233



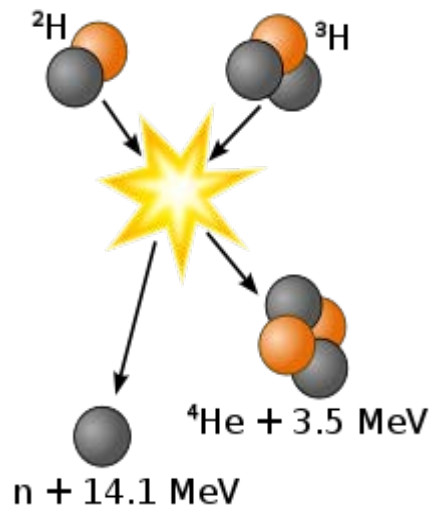
Fusion process

- Two light nuclear particles combine or “fuse” together by which energy is released.
- The product nuclei have less mass than the original particles.
- The mass difference is converted to energy at a rate governed by Einstein equation:

$$E = \Delta m \cdot c^2$$

- However, such fusion requires a very high temperature level (hundreds of millions deg.) to get started, which will be only available by fission reaction prior to fusion.

Fusion



Fusion reaction

- The possibility of release of large amount of nuclear energy can be seen by comparing the masses of nuclei of low atomic number.
- Suppose that one could combine hydrogen nuclei and two neutrons to form helium nucleus, in the reaction :



- The mass-energy difference (using atom masses) is :
- $[2(1.007825) + 2(1.008665)] - [4.002603] = 0.030377 \text{ amu}$
which corresponds to (28.3)MeV energy

Hydrogen bomb

Fusion is considered as uncontrollable reaction, and so for non-military application is not yet achieved.

As a weapon, hydrogen bomb is almost the only application recognized so far from fusion.

In the **Hydrogen bomb**, the very high temperature required for the fusion to take place is obtained by fission reaction, thus :

fission reaction → causes → fusion reaction to proceed

The resulting fusion reaction proceeds in a very rapid and uncontrolled manner. If this fusion reaction can be controlled, then utilization of inexpensive abundant fuel to produce huge amount of power will be most attractive.

Chapter Five

Nuclear Power Plant

5.04 - Nuclear Fuel

Nuclear Fuel

- Similar to fossil power plants, nuclear power plants produce steam to drive a turbine-generator set to make electricity. The heat source for today's nuclear power plants is **uranium** in contrast to combustion for the fossil units.

Type of reactions

- As seen earlier, energy is released from nuclear fuel by one of the following reactions:
 1. Fission
 2. Radioactivity
 3. Fusion
- In all of these reactions, a decrease in mass will result in an exothermic energy released. Such energy is utilized for various application most of which are for :
 1. Power generation.
 2. Military application.

Choice of fuel

- Since fusion controllable reaction is not yet achieved, fissionable fuel remains the only choice for nuclear power generation .
- Since fission can be caused by neutron strike, which is considered most appropriate for energy release
- And since that there are only few isotopes which are fissionable by neutron of all energies, and these are (U235, Pu239, U233).
- Then, these are considered as best choice of nuclear fuel for power generation application.

Uranium

- Uranium is the only substance occurring naturally which is fissionable.
- There are three uranium isotopes :
 - $^{92}\text{U}^{234}$** : uranium 234
 - $^{92}\text{U}^{235}$** : uranium 235
 - $^{92}\text{U}^{238}$** : uranium 238
- From these isotopes, only **uranium 235** is fissionable

Ore

Natural uranium (ore) is composed of

- * 99.3 % isotope (U238) non-fissionable,
- * 0.7 % uranium (U235) fissionable

Therefore, uranium ore contains a very low percentage of the desired atoms of the fissionable (U235) for nuclear fuel.

The fuel fabrication process includes steps to increase the fraction of (U235) from the natural availability of (0.7%) to a higher percentage of about (3-4 %)

The increase of natural uranium percentage is called “ enrichment process “



Uranium Ore (0.7%)

Uranium Enrichment

Enriched uranium is a kind of [uranium](#) in which the percent composition of [uranium-235](#) has been increased through the process of [isotope separation](#).

[Natural uranium](#) is 99.284% [U238 isotope](#), with U235 only constituting about 0.711% of its weight

The uranium metal must be:

1. extracted from the ore,
2. Purified, and
3. Prepared, for reaction
4. artificial *enrichment* to raise the fraction of U-235 to (3- 4)%.



Fuel Pellet (3.5%)

uranium dioxide

- The reactor fuel is uranium dioxide (UO_2), which is formed into a ceramic fuel pellet that is compatible with the water coolant.
- The fuel pellets are stacked into a Zircaloy clad fuel rod.
- Many fuel rods are placed in a square lattice to construct a fuel assembly (see Figure 1).
- A couple hundred fuel assemblies are generally needed to fuel the entire reactor core.
- The reactor core is housed in a reactor pressure vessel that is composed of steel 8 to 10 inches thick.

Fig.1

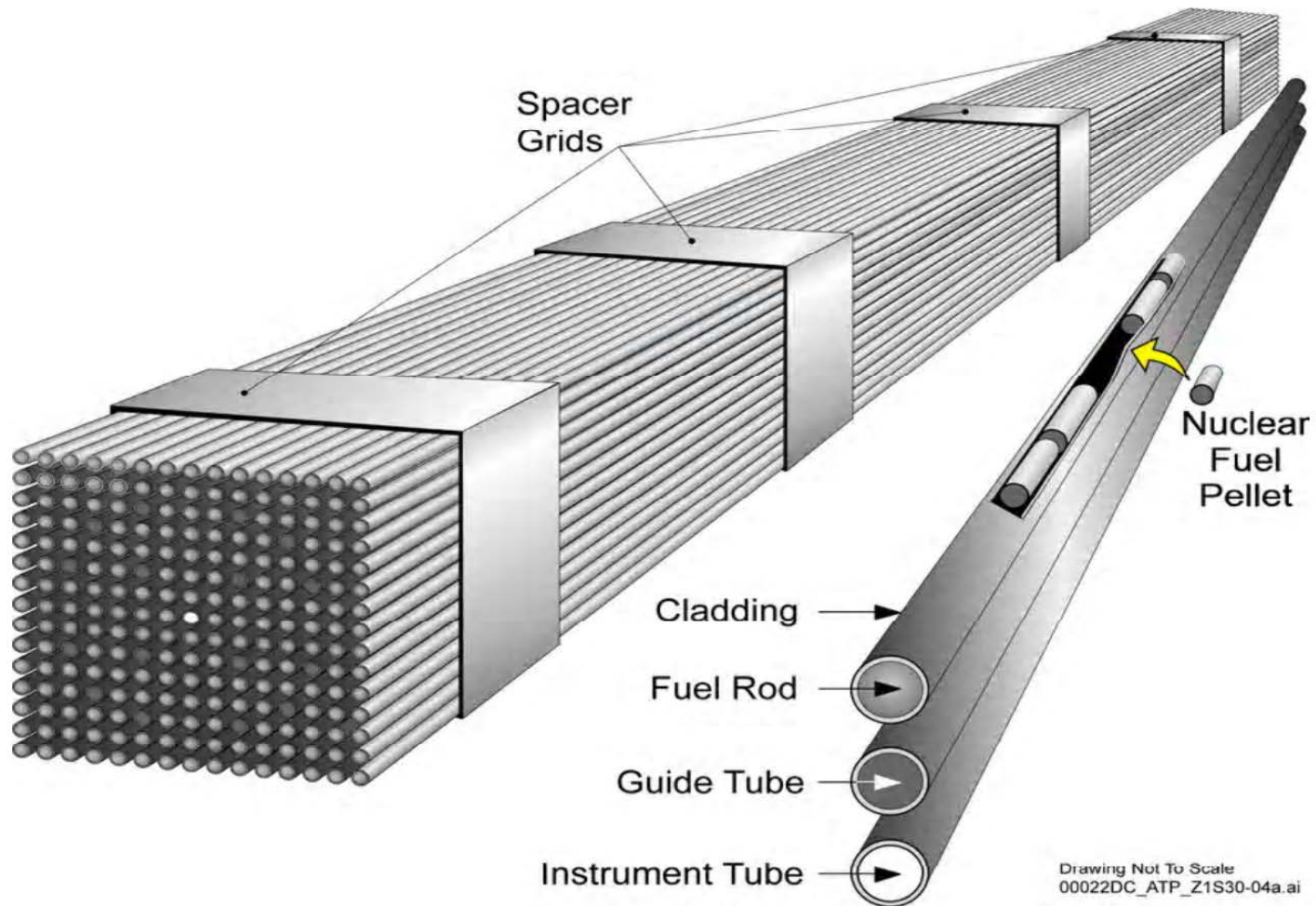
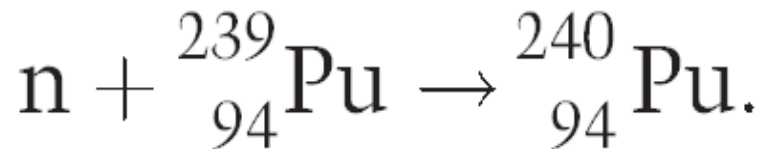
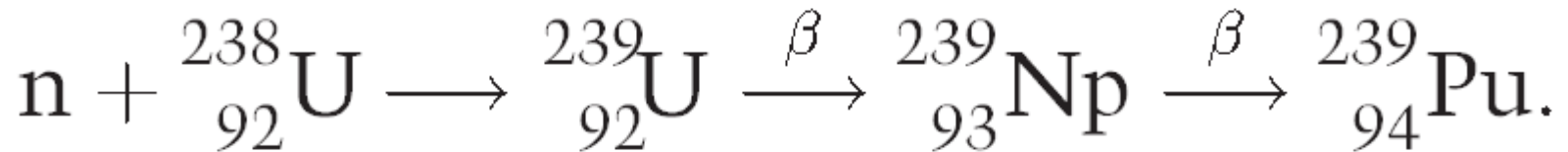


Figure 1. Nuclear fuel assembly with 15x15 array [source: DOE Office of Civilian Radioactive Waste Management, <http://www.ocrwm.doe.gov/>].

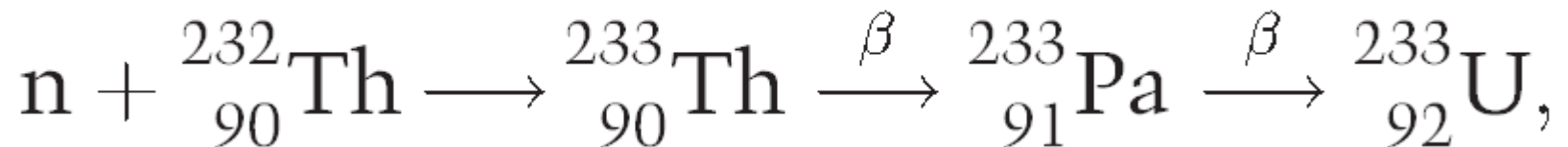
Plutonium Pu239

U238 capture a neutron, becomes radioactive and decay to **Pu239** which itself is radioactive. striking **Pu239** by a neutron produces **Pu240** which is fertile. Further neutron strike produces fissionable **Pu241**



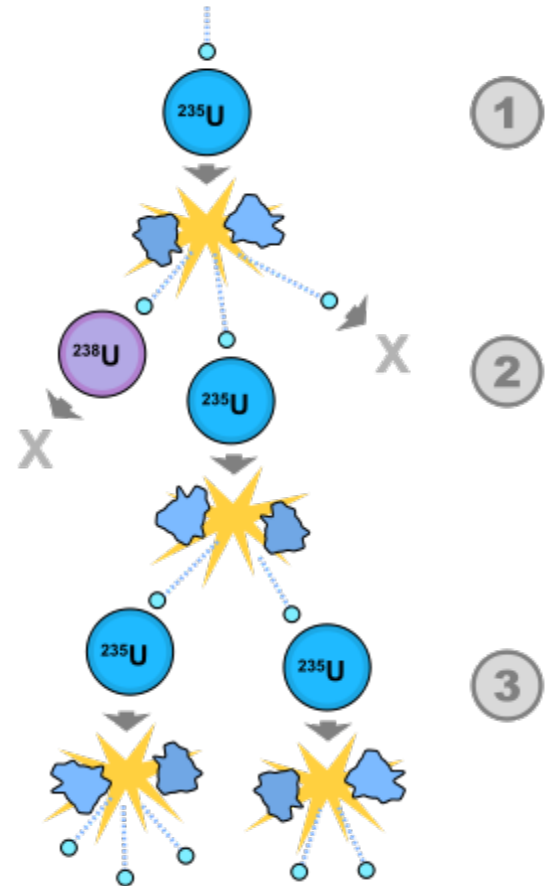
Uranium U233

- This is produced from thorium Th232, by neutron strikes



Chain reaction

- A schematic **nuclear fission** chain reaction.
- 1. A [uranium-235](#) atom absorbs a [neutron](#) and fissions into two new atoms (fission fragments), releasing three new neutrons and some binding energy.
- 2. One of those neutrons is absorbed by an atom of [uranium-238](#) and does not continue the reaction. Another neutron is simply lost and does not collide with anything, also not continuing the reaction. However one neutron does collide with an atom of uranium-235, which then fissions and releases two neutrons and some binding energy.
- 3. Both of those neutrons collide with uranium-235 atoms, each of which fissions and releases between one and three neutrons, which can then continue the reaction.



conclusions

- Fuel of a nuclear reactor should be fissionable material, when strikes by neutron undergoes nuclear fission and thus producing chain reaction.
- U235 is most unstable type, capable of sustaining chain reaction, and therefore it is referred to as “primary fuel”.
- Pu239 & U233, are artificially produced from U238 & Th232 respectively, and are called “secondary fuel”.
- Pu239 and U233 so produced can be fissioned by thermal neutrons.

Chapter Five

Nuclear Power Plant

5.05 - energy

Einstein's Law

- One atom may be transformed into another by losing or acquiring some of its sub-particles. Such reaction results in a change in mass and therefore release or absorb energy (ΔE).
- According to Einstein's law :
 - $\Delta E = (1/g_c) \cdot \Delta(m \cdot c^2)$
 - Where
 - $1/g_c$: conversion factor
 - m : reactants mass
 - c : speed of light in vacuum
- This equation is applicable to all processes “ physical , chemical , nuclear “
- Such energy is classified as nuclear when it is associated with changes in the atomic nucleus.

Mass and energy are inter-convertible, where the disappearance of (m) gm of a matter would generates $(m.v^2)$ ergs of energy, where:

V : is the velocity of light (cm/s)

Example - 1

$$m = 1 \text{ gm}$$

$$v = 2.988 \times 10^{10} \text{ cm/s}$$

Therefore

$$E = 1 \times [2.988 \times 10^{10}]^2 \text{ ergs}$$

$$E = 1 \times [2.988 \times 10^{10}]^2 \times 10^{-7} \text{ J}$$

$$E = [1 \times [2.988 \times 10^{10}]^2 \times 10^{-7}] \times 10^{-6} \text{ kW.hr}$$

$$E = 25 \times 10^6 \text{ kW.hr}$$

This means that (1 gm) of matter is equivalent to (25) million of (kw.hr)

Examples - 2

1. Atomic bomb --- almost pure U235 (90% of ore)
2. Reactor fuel --- natural uranium enrichment with U235 (3-4 %) of ore.
3. Fertile material --- U238, which means that uranium fertilization by :
U238 + absorbing neutron $\rightarrow\rightarrow$ fissionable plutonium Pu239

Energy calculation

1 - Avogadro's hypothesis

equal volume of all gases under same conditions of (T & P) contains the same number of molecules.

this number of molecules is called Avogadro's number N_{Av}

$$N_{Av} = 6.023 \times 10^{23} \quad \text{molecules/gm.mole}$$

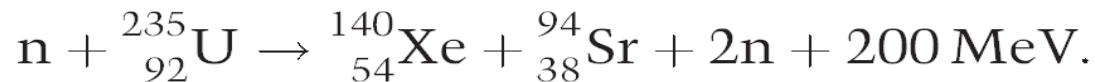
$$N_{Av} = 6.023 \times 10^{26} \quad \text{molecules/kg.mole}$$

2 – fission

If one neutron runs into a U235 nucleus, this nucleus will absorb the neutron, become unstable; splits; and fracture immediately .

3 – nuclear reaction

from this reaction, neutrons are expelled and energy is produced



4 – energy produced per fission is (200 MeV)

5 – one MeV = {1.6 x (10**⁻¹³)} J

6 - number of U235 atom that must be fissioned per second to produce thermal power of (1 W) is :

$$N_f = \left[\frac{1W}{200 \frac{\text{MeV}}{\text{fission}}} \right] \left[\frac{\text{J/s}}{W} \right] \left[\frac{1 \text{ MeV}}{1.6022 \times 10^{13}} \right]$$

$$N_f = 3.12 \times 10^{10}$$

This means that to produce (1J) of energy requires (3.12 x 10**¹⁰) of U235 atoms to be fissioned per second.

7 – the equivalent mass of material (Meqv)

Nav = 6.023 x 10**²³ atom/gm.mole

for U235 = 235 gm/gm.mole

$$M_{eqv} = \frac{235 \frac{\text{gm}}{\text{gm mole}}}{6.023 \times 10^{23} \frac{\text{atom}}{\text{gm mole}}}$$

8 – from 6 & 7, the mass (M) of U235 /J

$$M = M_{eqv} \times N_f$$

$$M = \left[\frac{235}{6.023 \times 10^{23}} \right] [3.12 \times 10^{10}]$$

$$= 1.22 \times 10^{-11} \text{ gm U235/J}$$

9 – for 1MW/day multiply by $\left[10^6 \frac{J}{MW} \right] \left[86400 \frac{sec}{day} \right]$

$$= \text{multiply by } [0.864 \times 10^{11}]$$

therefore

$$M = [1.22 \times 10^{-11}] [0.864 \times 10^{11}]$$

$$M = 1.054 \text{ gm/day}$$

This means that about (1 gm) of fuel is used per (1MW-day) of useful thermal energy released. So, in a typical reactor which produces (3000 MW) of thermal power, the U235 fuel consumed is about 3kg/day.

To produce same energy by the use of fossil fuel (coal, oil, gas), millions of times as much weight would be required.

conclusion

1 - U235-n corelation

- == x_n is freed , and 1_n absorbed
- == if there is no other U235 atom around, then $(x-1)_n$ will fly away in space
- == but, the fissioned U235 is part of mass of uranium, and therefore, there will be plenty of U235 atom available for the flying $(x-1)_n$ to collide with
- == from each (U235-n) collision, another $(x-1)_n$ are freed for the second fission
- == and so, for the 3rd & 4th ...etc
- == this continuous process is “chain reaction”.

2 – fission time

Chain reaction means a process of continuous “capturing neutrons & nucleus splitting “ in such a very fast rate, which is in the order of (1 picoseconds), where

1 picoseconds = (1×10^{-12}) second

3 – mass of U235

i- critical mass

only one of the free (n) collides with U235 and cause it to split for each fission, the mass of U235 is said to be “critical” , and the temperature is stable.

ii- subcritical mass

Less than one of the free (n) hit another U235, then the mass is “subcritica” , and eventually fission will end.

iii- supercritical

More than one of the free (n) hit another U235, then the mass is “supercritical” , and the reactor will heats up.

4 – reactor – bomb

i- nuclear bomb

Requires very supercritical U235 mass, so all of the U235 atoms split in a single microsecond.

ii- nuclear reactor

Requires slightly supercritical mass, so plant operators can raise and lower reactor temperature by some means of control (control rod) .

Chapter Five

Nuclear Power Plant

5.06 – structure & components

introduction

- Nuclear reactor is an apparatus in which heat is produced due to nuclear fission chain reaction.
- A nuclear power plant is a very complex system, where thousands of valves and pumps; miles of tubing and electrical wiring; and many tons of rebar and structural steel are all required.
-

63



Plant structure

There are three major buildings that make up the plant structure :

1 - Containment building

houses the reactor and it's high pressure steam generating system.

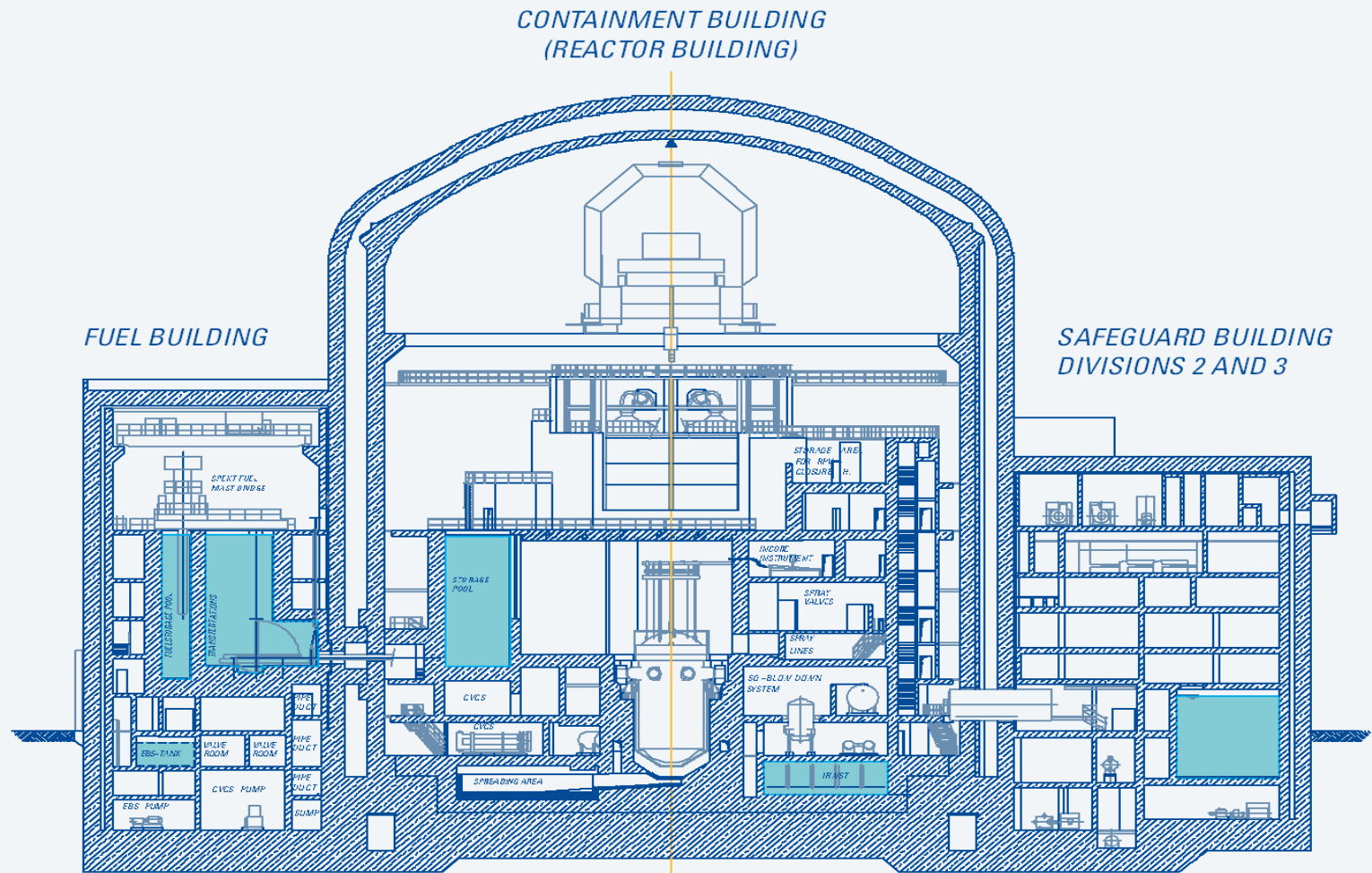
2 - Turbine building

houses the steam turbines, condensers, and electrical generator.

3 - Auxiliary building

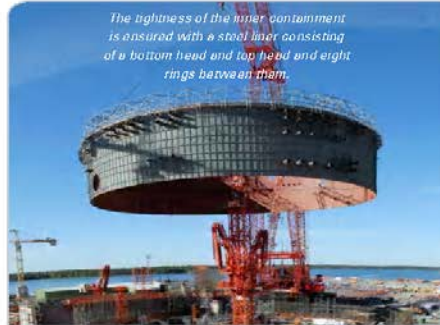
houses normal and emergency support systems, such as the residual heat removal system. Fuel handling and storage equipment, laboratories, maintenance areas, and control room.

4 – depending upon the plant location and environmental regulations, there may or may not be **cooling tower** to remove excess heat from the facility.



Steel structure





Reactor major parts



1. Nuclear fuel
2. Moderator
3. Control rod
4. Reflector
5. Reactor vessel
6. Biological shielding
7. Coolant
8. Reactor core

1 – nuclear fuel

- Nuclear fission is the basis of most commercial reactors, so the fissionable type of fuel previously mentioned (U^{235} , Pu^{239} , U^{233}) will be considered.
- Nuclear fuel should be :
 - * inexpensive
 - * operate at high temperature
 - * resist radiation damage
- Nuclear fuel may either one of
 - * uranium oxide (UO_2) - brittle ceramic
 - * uranium carbide (UC) – black ceramic

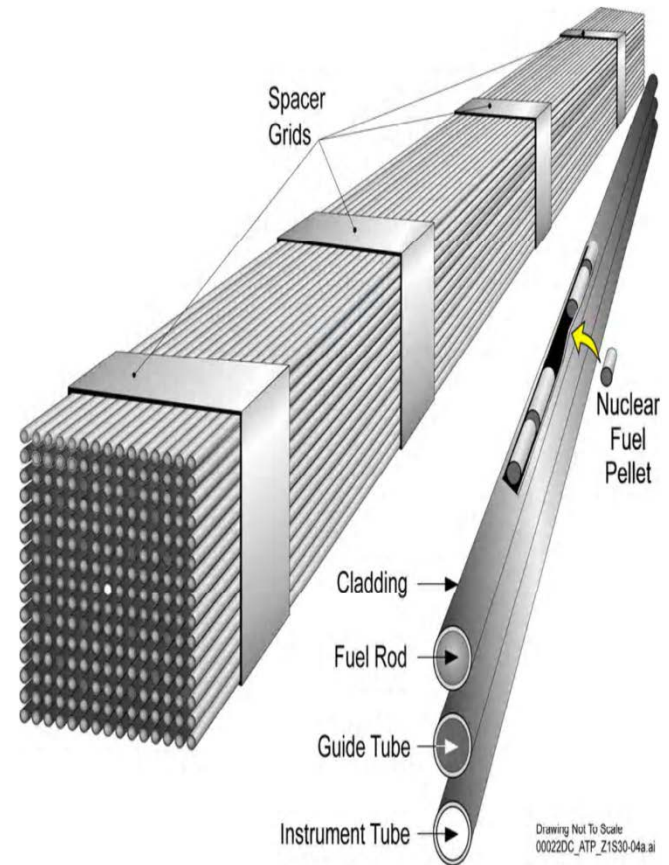
Fabrication of nuclear fuel

- The enriched U235 or UO₂ is typically formed into 2.5cm long **pellets** of about 1cm diameter.
- These pellets are then arranged into 12ft long slender metal tube, generally made of zirconium alloy (zircaloy). Such tubes are called **“fuel cladding”**.
- **When a tube is filled with the uranium pellets, it is pressurized with helium gas, and plugs are installed and welded to seal the tube. The filled rod is called “fuel rod”**



Fuel Pellet (3.5%)

- The fuel rods are bundled together into “**fuel assemblies**” or “fuel element, and ready for installation into the reactor vessel.
- The fuel assemblies at the instance of installation consist of :
 - * **fuel rods**
 - * **spacer grids**
 - * **upper and lower end fittings.**
- Fuel rods are arranged in a square matrix ranging from (8x8) to (17x17).



2 - moderator

- In a chain reaction, the neutrons produced are fast moving objects.
- These fast moving neutrons are less effective in causing U235 fission, tending to escape from reactor.
- Reducing the speed of these neutrons is thus important to enable its utilization. Such is done as follows :
 - i- colliding them with nuclei of other lighter material which does not capture but scatter them.
 - ii- each of such collision causes a loss in energy, resulting in overall speed reduction.
 - iii- such material is called “moderator”
- the slowed down neutron so produced are then easily captured by nuclear fuel and chain reaction will proceed smoothly.
- Types of moderators generally used are any of the following materials :
 - 1- graphite
 - 2- heavy water
 - 3- beryllium



Graphite moderated reactor

3 – Control Rod

Since the nuclear reactor usually contains as much fuel as is sufficient to operate a large power plant for several months.

Then, the consumption of this fuel and the power level of the reactor depends upon its “neutron flux” in the reactor core.

the energy produced in the reactor, due to fuel surplus availability, by fission process during chain reaction may reach a very high level, if not controlled, will cause a very high heat energy released and thus the entire core surrounding structure will eventually melt down, resulting in a radioactive fission products to escape out of the reactor.

Therefore, some mean of control, is a must requirement, to prevent overheating and the dangerous after period.

Control rods are made of materials “that absorb neutrons” such as “boron or cadmium”, fabricated in the form of cylindrical shape (sometimes sheet form) that can be moved in and out of the reactor core assembly using appropriate lifting mechanism.

Raising and lowering the control rods allow the operator to control the rate of the nuclear reaction, i.e

1- raising the control rods, results in reducing neutron absorption, and therefore allowing for more rate of fission to take place, thus releasing more heat energy.

2- lowering the control rods, increases the number of neutrons absorbed and this reduces the rate of fission process, and so produces less heat energy.

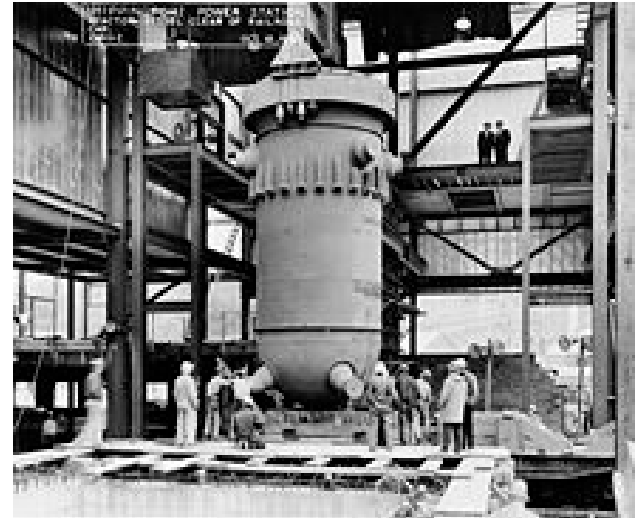
3- if the rods are lowered completely into the uranium bundle, the reactor will be shut down. This is done in an emergency conditions.

4 – Reflector

- The neutrons produced during fission process will be partly absorbed by:
 - 1- fuel rods
 - 2- moderator
 - 3- coolant
 - 4- structural materials
- The unabsorbed neutrons try to escape from reactor core and therefore will be lost. Such losses should be minimized to improve fission probability rate.
- to prevent the loss of these neutrons, the reactor core is surrounded by a material called “reflector”.
- The reflector send neutrons back into the core, and these will cause more fission. Therefore, improves the neutrons economy of the reactor.
- Generally, reflectors are made of graphite & beryllium.

5 – Reactor vessel

- the **reactor vessel** is a pressure vessel containing the coolant and reactor core.
- It is a device for containing and controlling a chemical reaction. The chemical process enables to convert raw material into final product under given pressure and temperature.
- During the reaction it becomes necessary to remove excess heat in the process to enable keep process under control.
- Vessels are built to withstand high pressure in the system.



6 – reactor core

- The nuclear reactor core (also referred to as the "reactor core", or the "core") is the region within a nuclear reactor where the nuclear fuel assemblies are located and the nuclear reaction consequently takes place.
- Inside the core are pencil-thin nuclear fuel rods, each about 12 feet (3.7 m) long, which are grouped by the hundreds in bundles called "fuel assemblies". Inside each fuel rod, pellets of uranium, or more commonly uranium oxide, are stacked end to end. Also inside the core are [control rods](#), filled with pellets of substances like [cadmium](#) that readily capture [neutrons](#) .

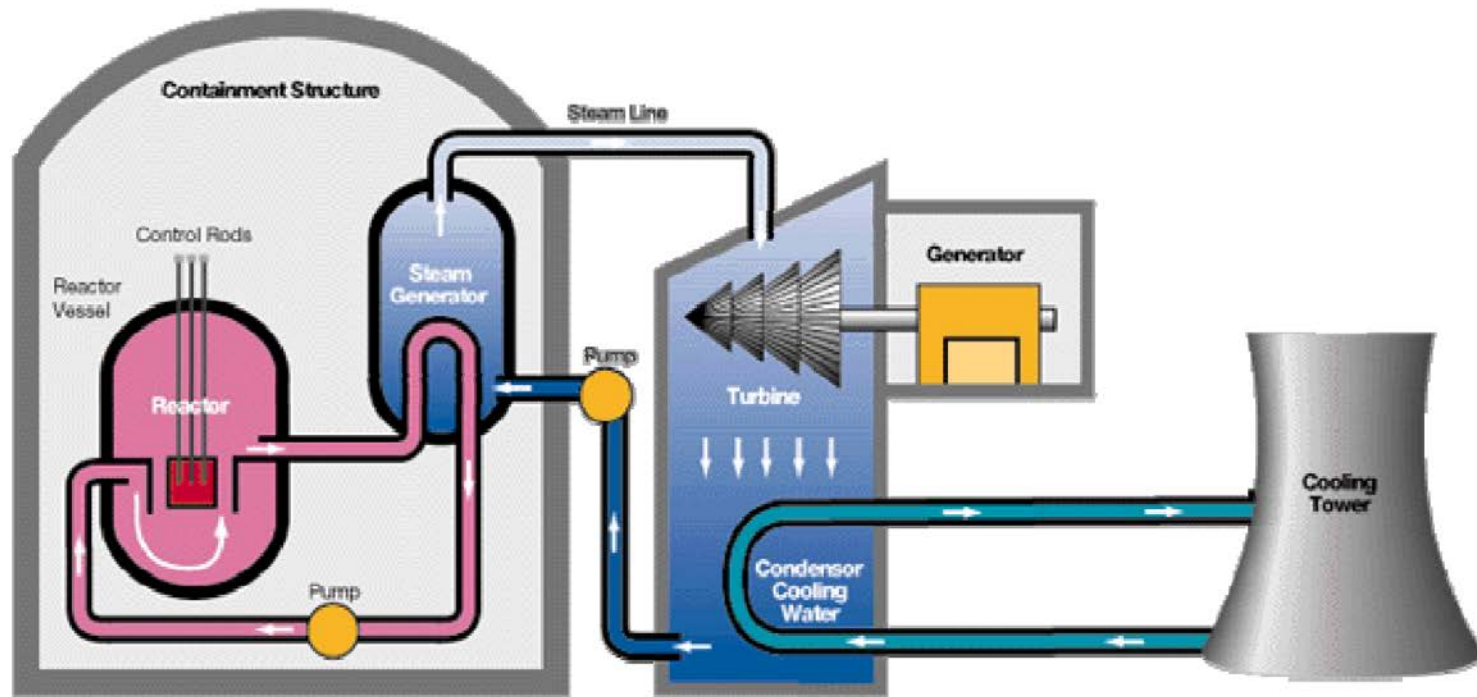
7 - Coolant

- There are two main types of coolant system in the nuclear power plant, namely :
 - 1 – pressurized water reactor
 - 2 – boiling water reactor

Pressurized water reactor

- **PWRs** utilize two coolant loops with an intermediate heat exchanger (steam generator).
- The reactor core heats the primary reactor coolant (water) to about 600°F at which point it flows to the steam generator.
- After transferring its heat to the secondary water in the steam generator, the temperature of the primary coolant is reduced to about 540°F.
- The reactor coolant is then circulated by a pump back to the reactor core.
- The reactor coolant is kept at a pressure of about 2200 psia which prevents the primary coolant from boiling.
- The secondary water, which receives the transferred heat, is changed to steam that is piped to the turbine.
- The remainder of the plant is very similar to a large coal-fired unit in that the exiting steam from the turbine is condensed and sent back to the steam generator via feedwater heaters and pumps

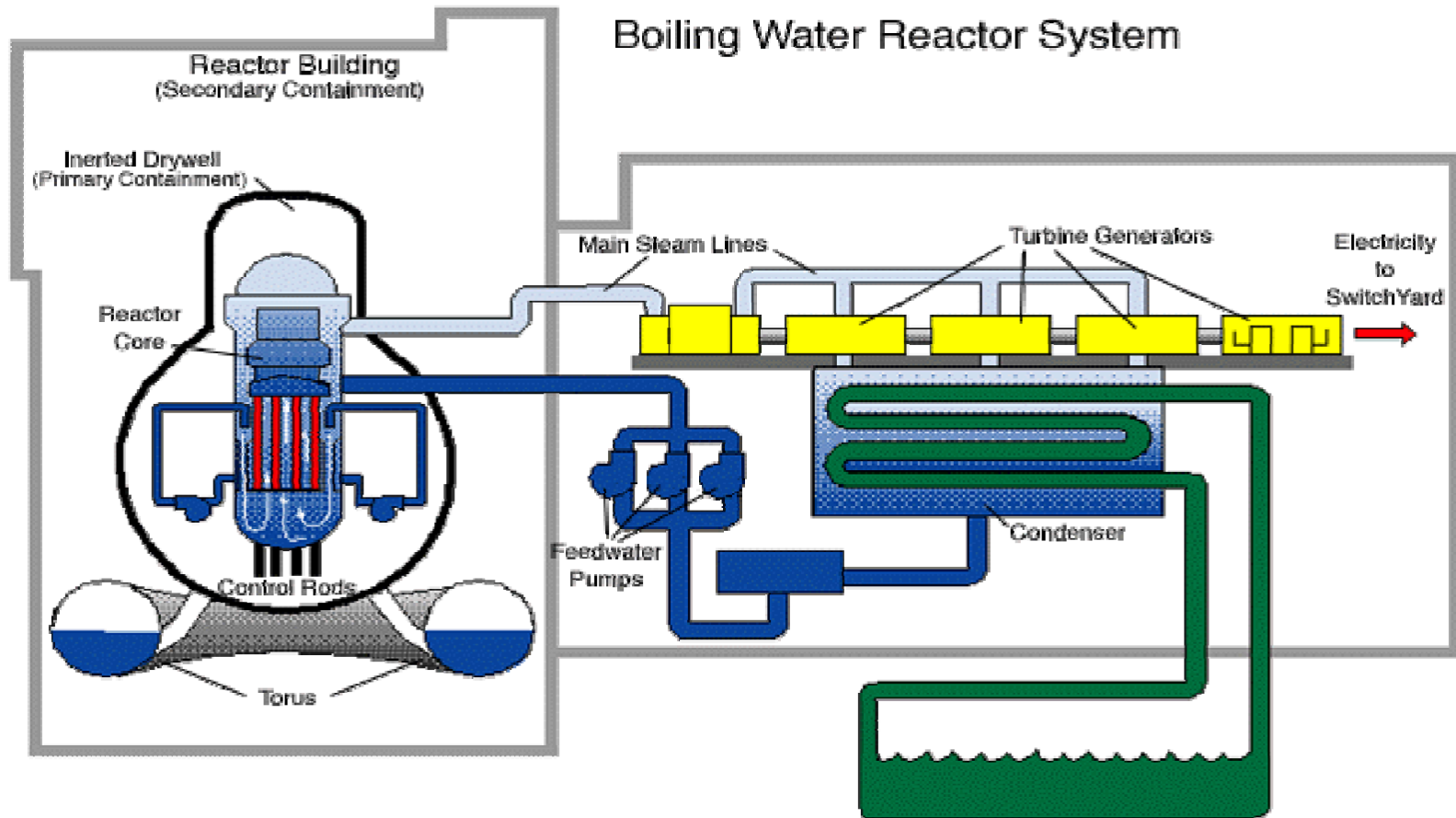
Pressurized water reactor



Boiling water reactor

- **BWRs** utilize a single coolant loop and therefore boil water in the reactor core.
- The produced steam is sent directly to the turbine .
- The steam pressure is about 1100psia, which corresponds to a steam temperature of 556°F.
- Jet pumps at the reactor pressure vessel provide forced coolant circulation through the reactor core.

Boiling water reactor

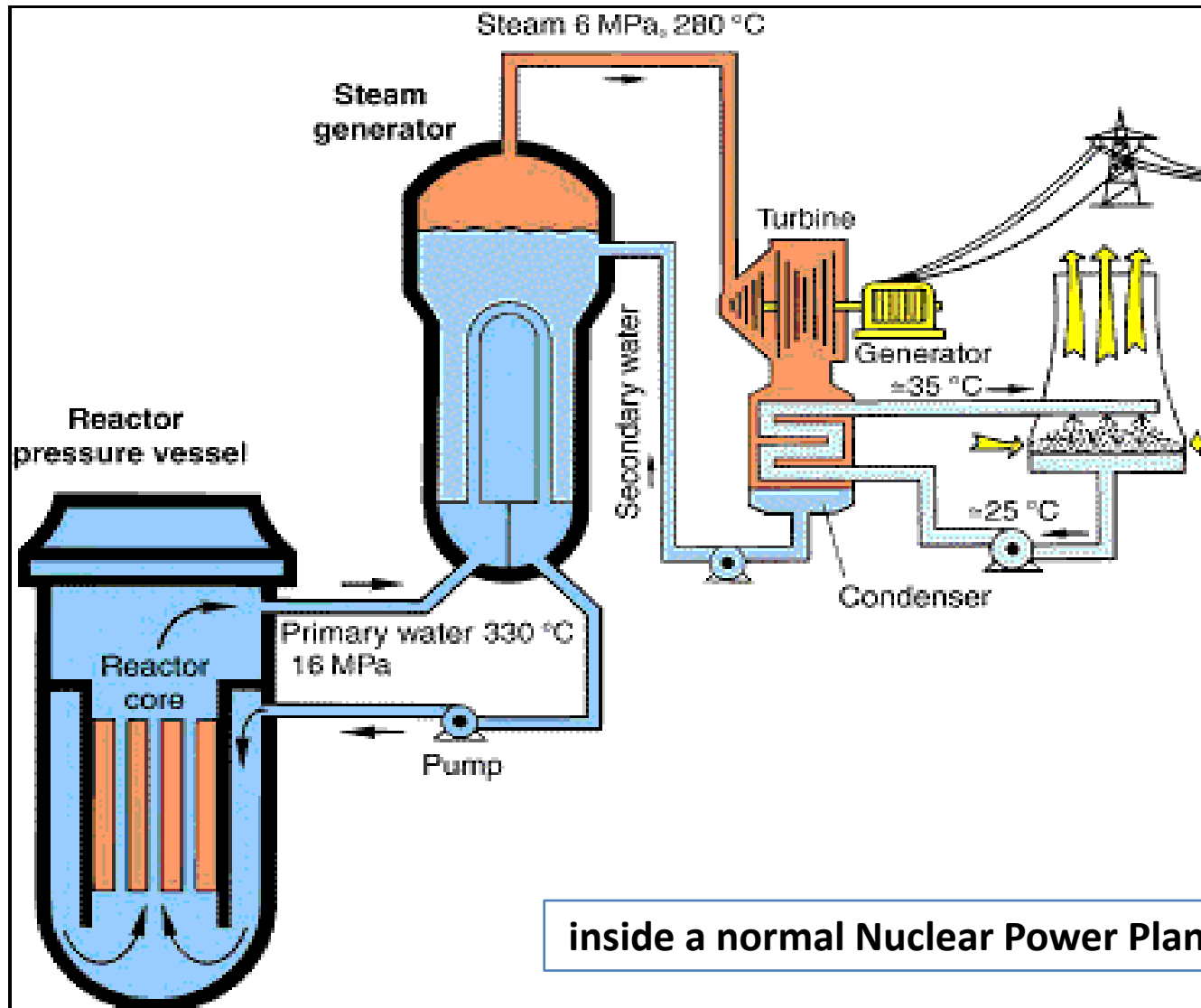


Chapter Five

Nuclear Power Plant

5.07 - Inside Nuclear Power Plant





inside a normal Nuclear Power Plant



Outside a normal Nuclear Power Plant

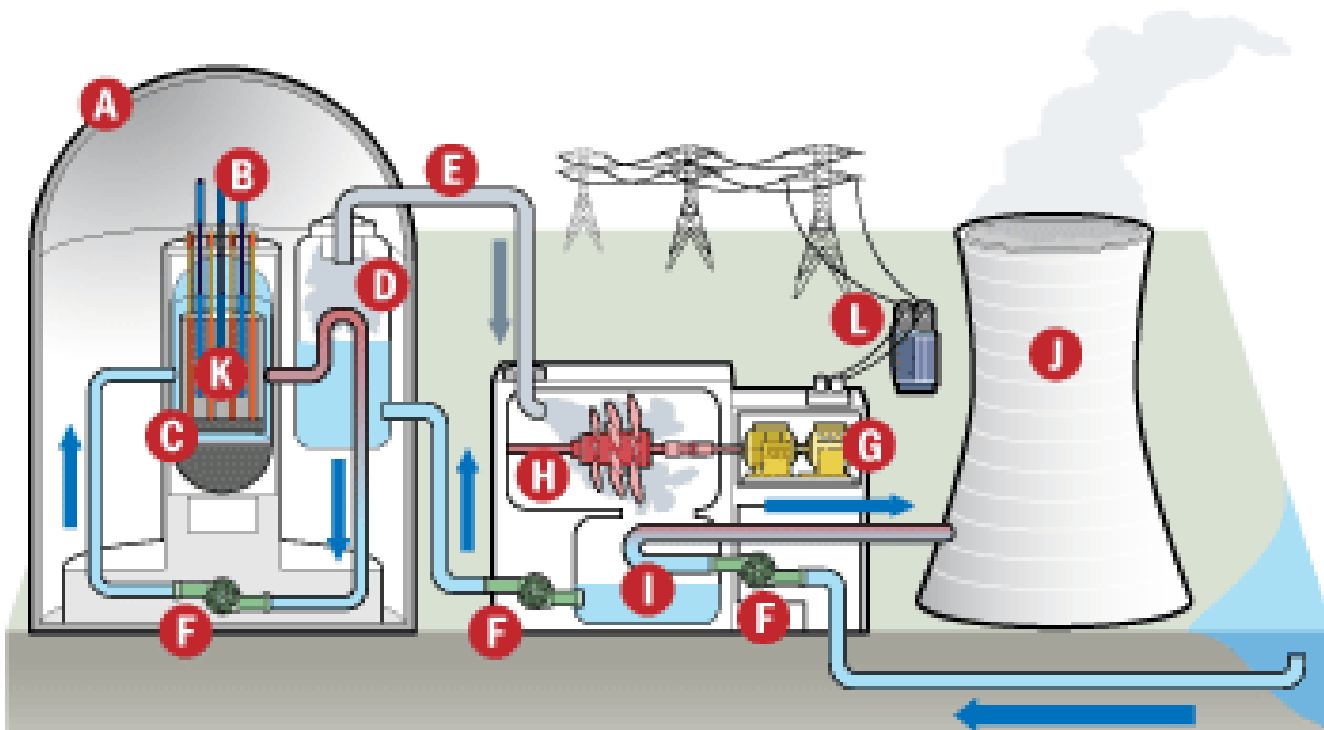
**If not careful
You get**



Outside Nuclear Power Plant

Inside a Nuclear Power Plant

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A Containment Structure

B Control Rods

C Reactor

D Steam Generator

E Steam Line

F Pump

G Generator

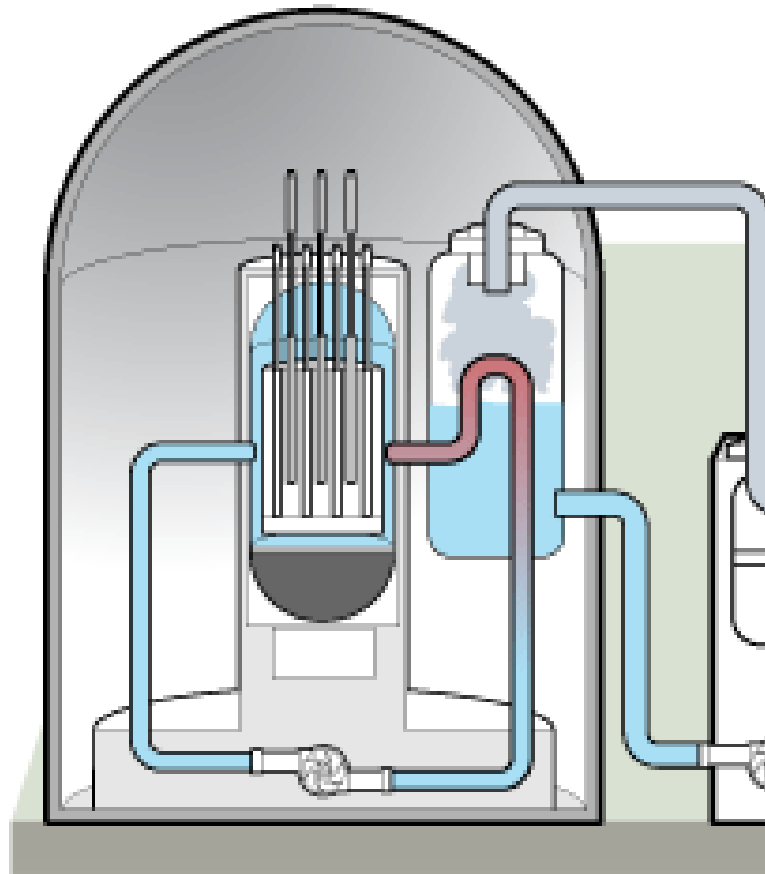
H Turbine

I Cooling Water Condenser

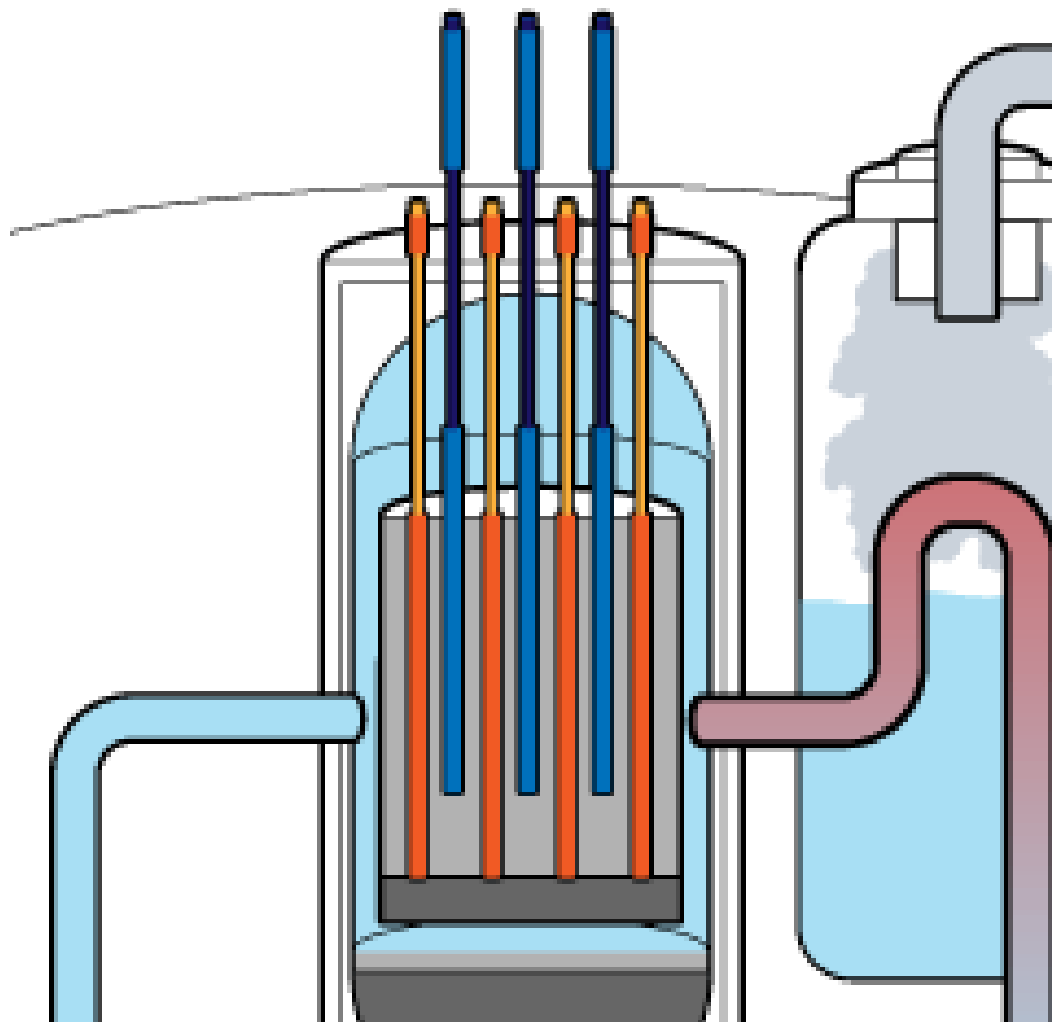
J Cooling Tower

K Fuel Rods

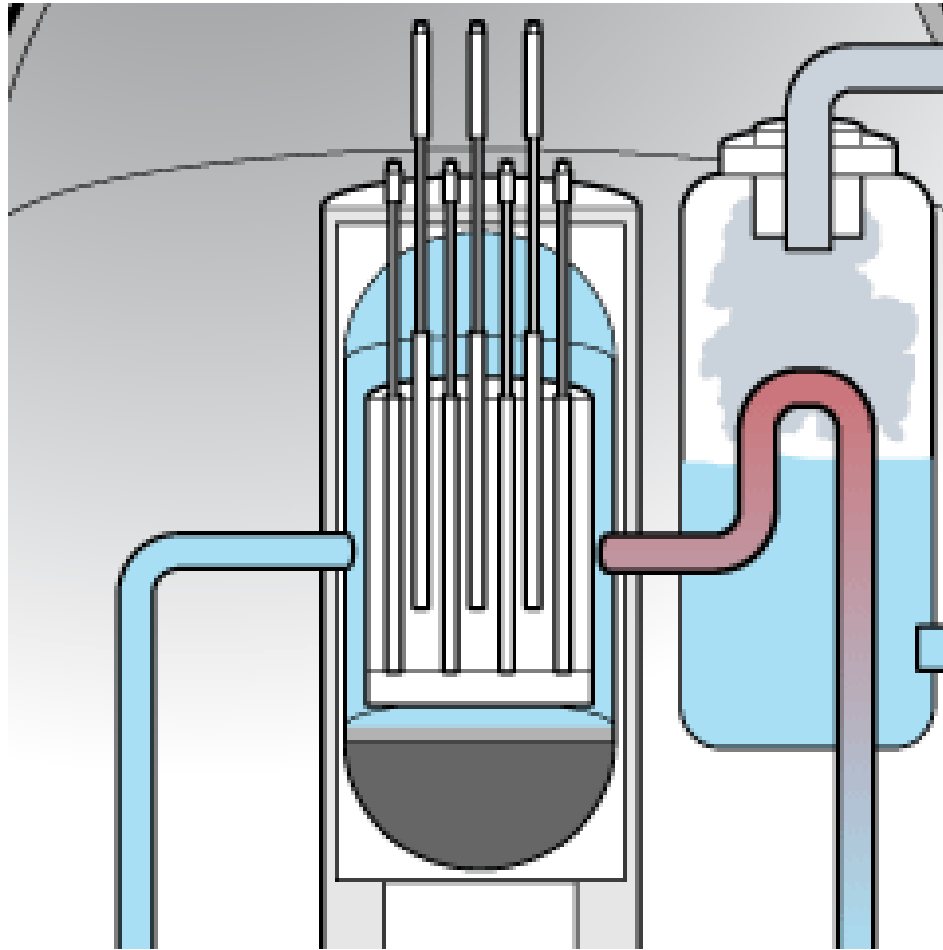
L Transformer



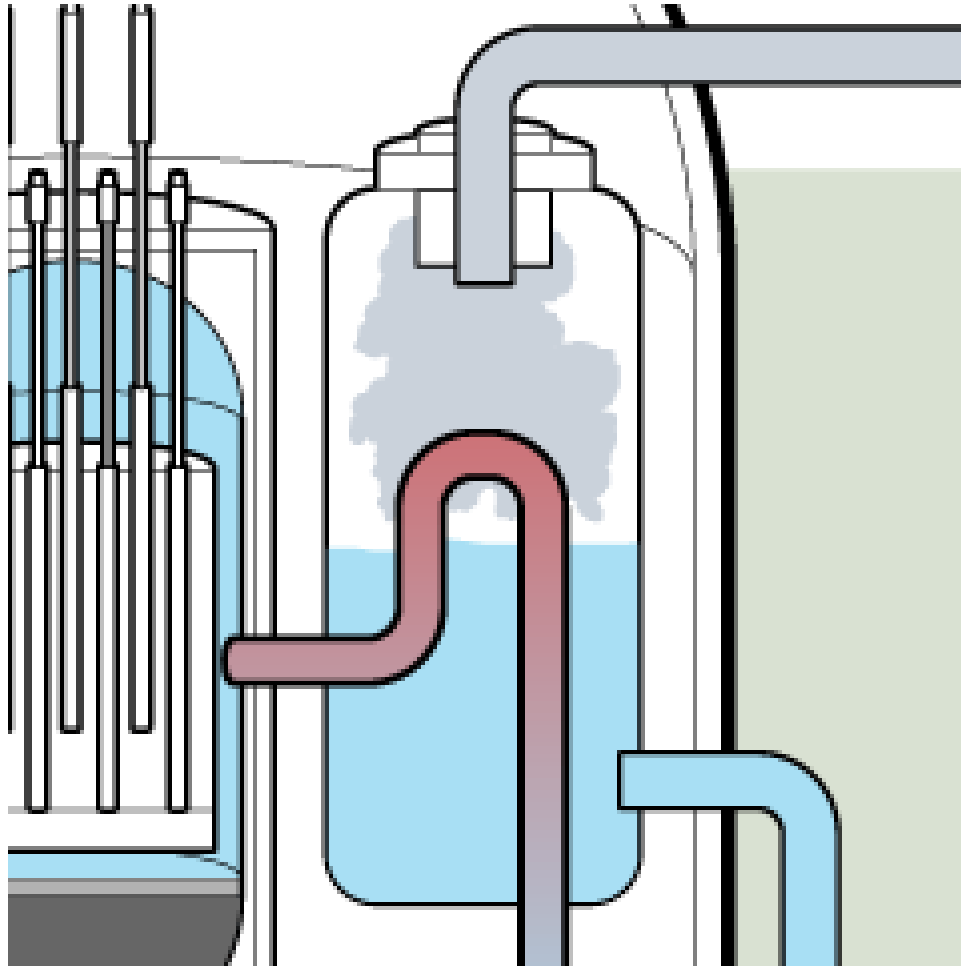
This is pretty much ground zero for a nuclear reactor. The overarching structure is called the containment vessel. With its layers of thick concrete and steel, it's intended to protect against radiation leaking into the environment. You can also see the reactor itself.



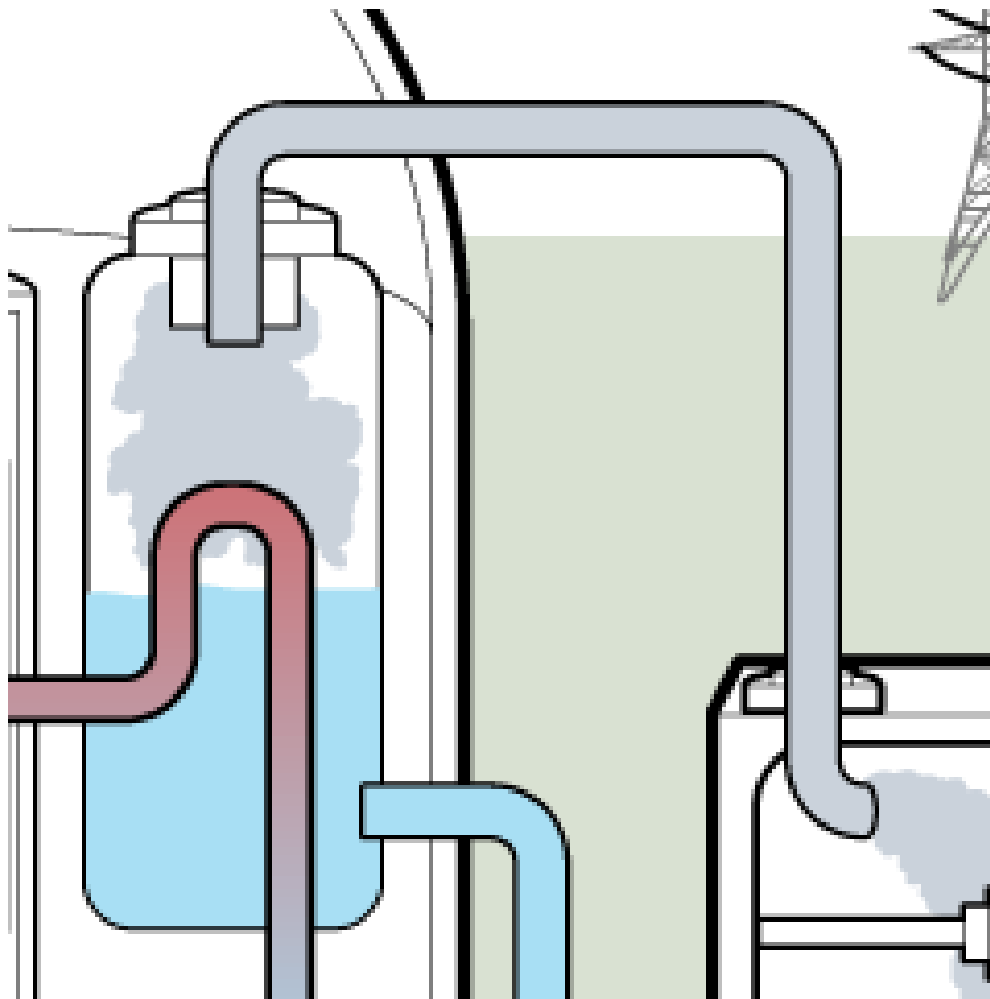
Now we're looking at the very core of the reactor, the coolant-filled vat where the fuel and control rods are located. The fuel rods are drawn in red and the control rods are blue. Moving the control rods regulates the rate of the nuclear reaction (and the heat generated). Submerging the control rods shuts down the power plant completely.



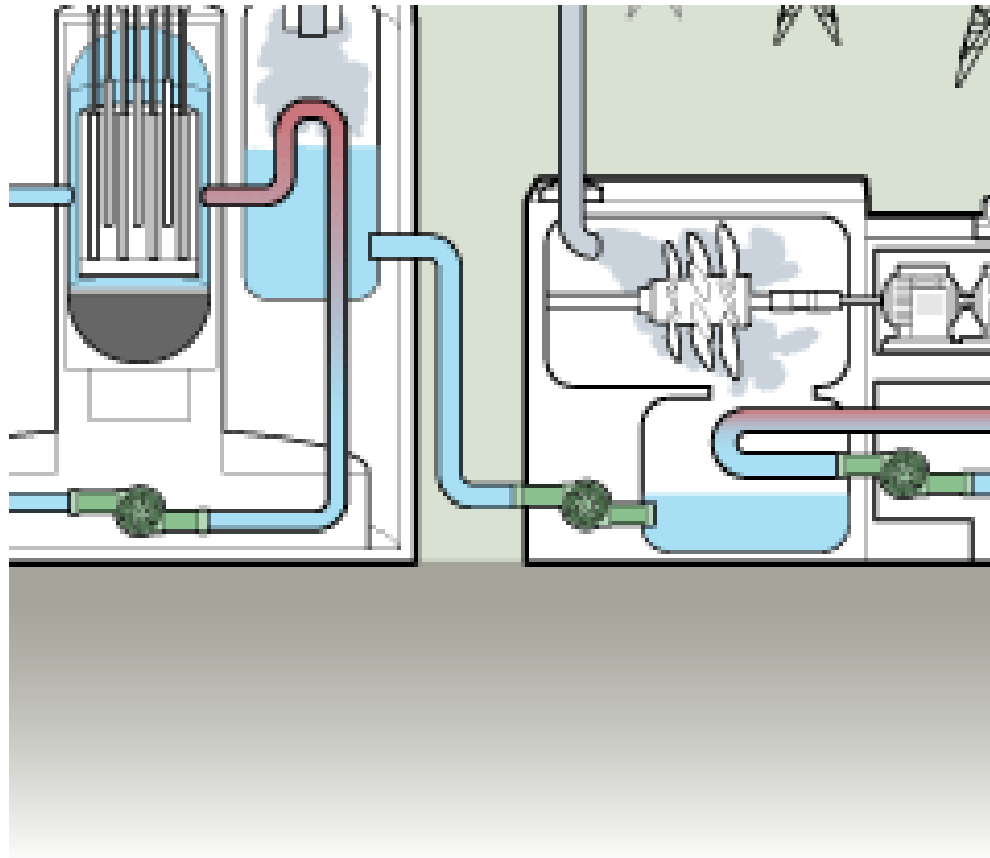
The blue pipe on the left pumps cold coolant into the reactor core while the red pipe on the right draws hot coolant into the steam generator, the second vessel you see here. The pumps that keep coolant flowing throughout the system are critical to the safe functioning of a nuclear reactor.



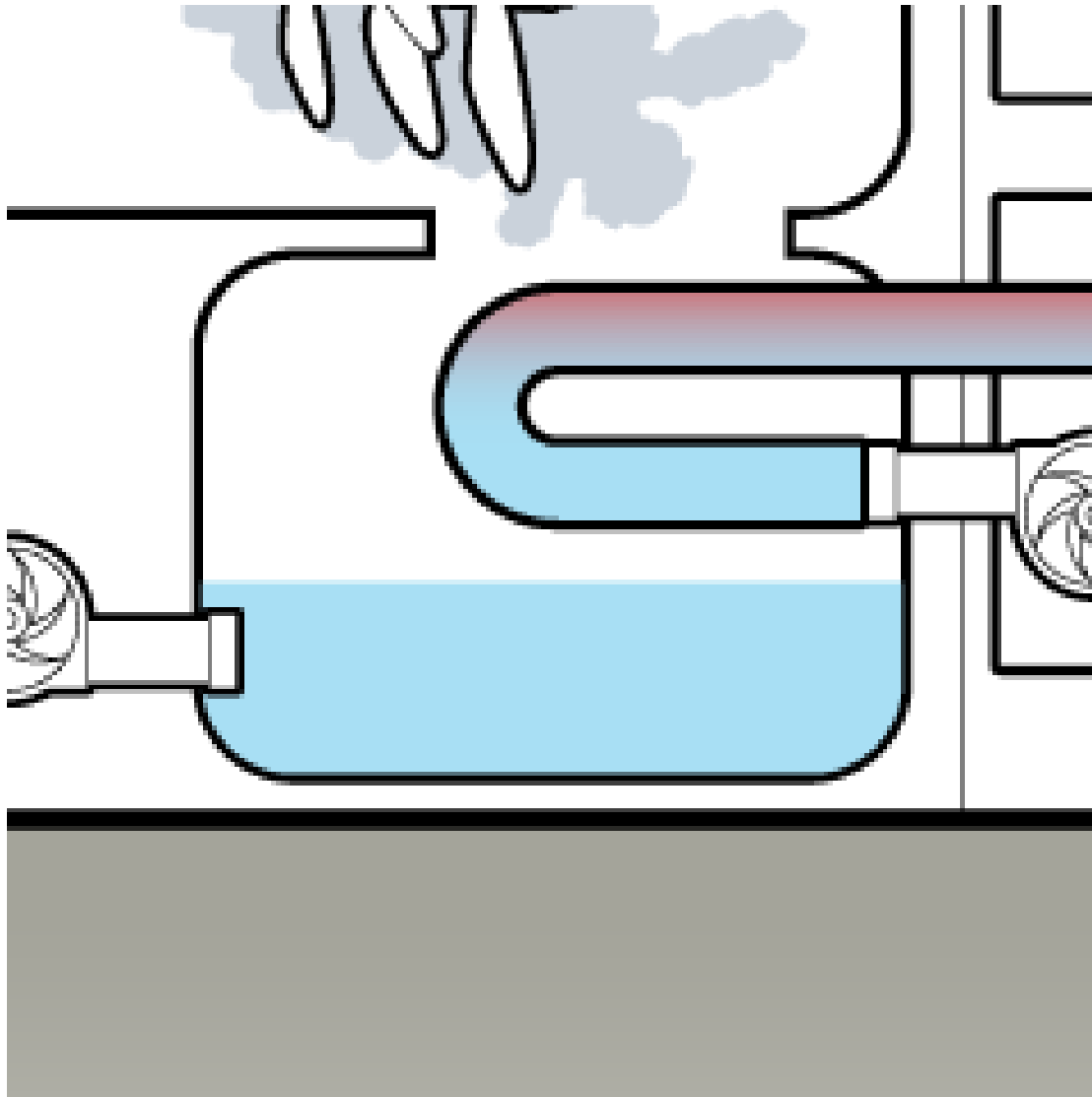
The steam generator then sends the collected steam to the turbine by way of a steam line (at top).



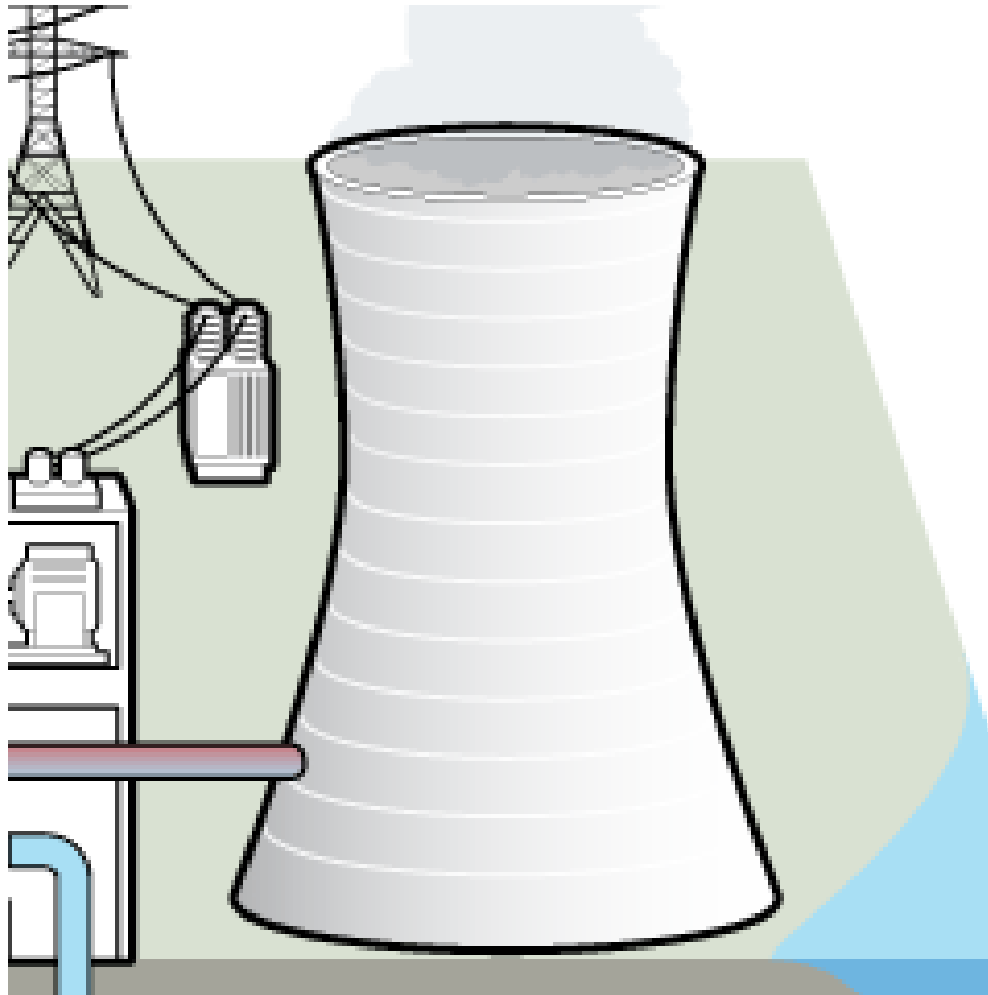
At last, the steam drives a turbine.



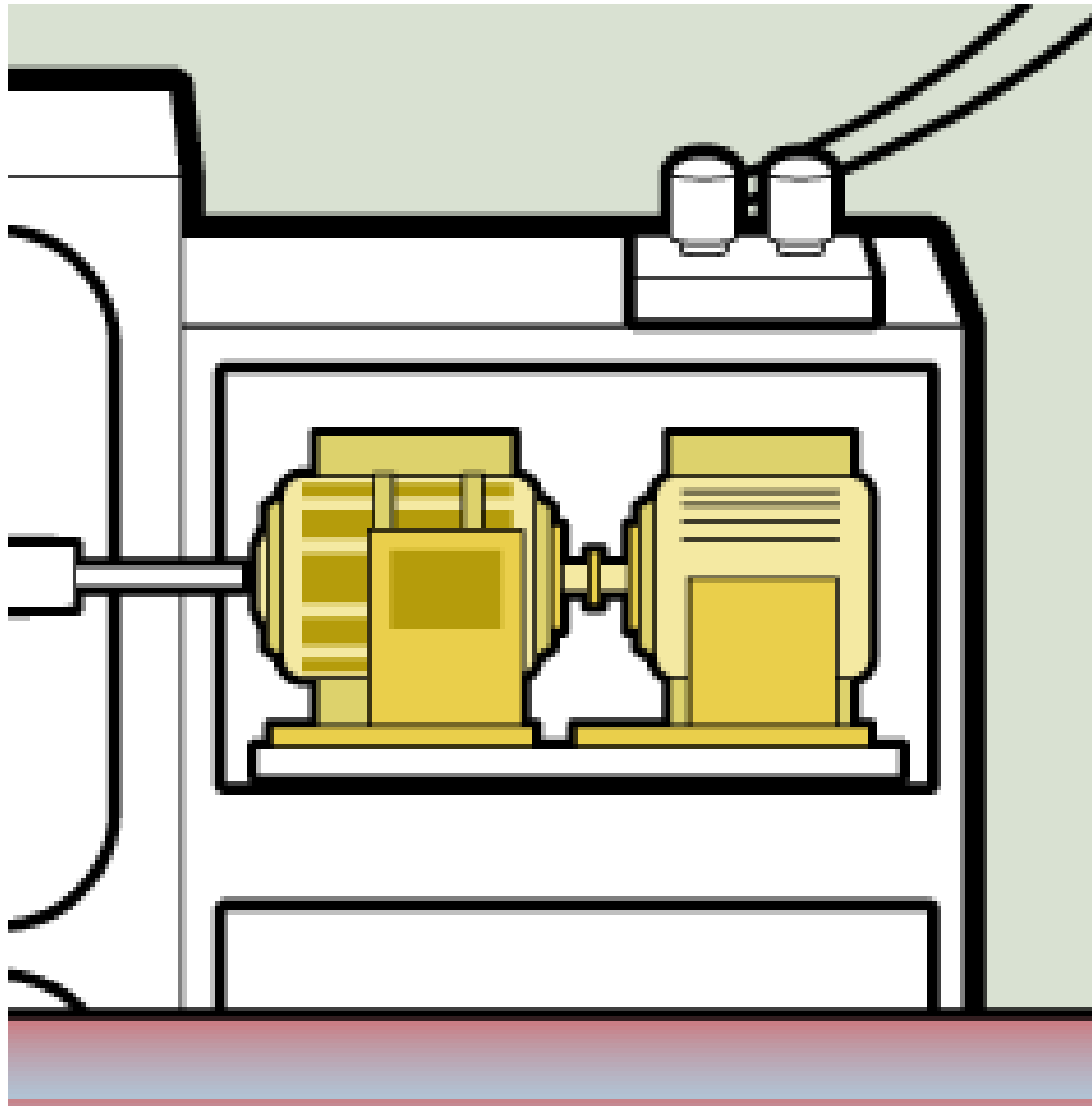
In this picture, we get a good look at the turbine (above) and the cooling water condenser (below). The condenser ultimately will send the newly cooled liquid it produces back to the steam generator to maintain the core temperatures needed there.



The cooling water condenser also sends coolant to the coolant tower.



The coolant tower does what its name implies -- decreases the temperature of the liquid moving through it so it's ready to head back toward the condenser or, in some models, be discharged into the environment. The vapor that you see rising from a cooling tower is just ordinary water.

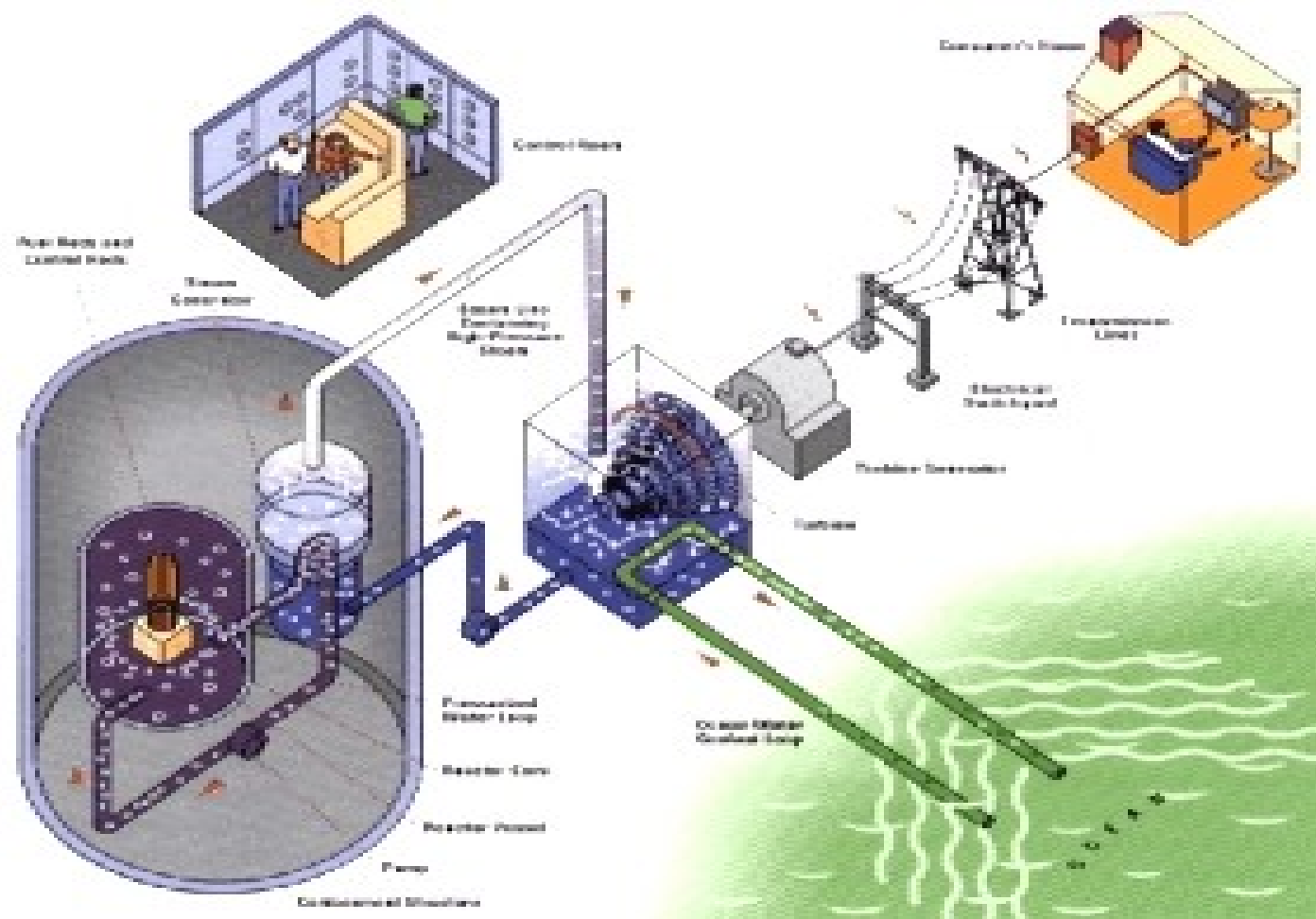


Electricity generation

Chapter Five

Nuclear Power Plant

5.08 - classification



Nuclear Power Plant can be classified in general according to the followings :

1. Type of nuclear reaction.
2. Moderator materials.
3. Coolant application system.
4. Reactor generation (age)
5. Phase of fuel.
6. Application and usage.

1 – type of nuclear reaction

- I – nuclear fission.

most commercial reactors are based on nuclear fission, and this is divided roughly into two classes:

a/ thermal reactor (slow neutron reactor)

almost all current reactors are of this type, where it uses slowed or thermal neutrons, which is characterized by :

- * high probability of fissioning the fissile nuclei U235
- * low probability of capturing neutron by U238.

b/ fast neutron reactor

it uses fast neutrons, which is characterized by:

- * no moderator required.
- * requires highly enriched fissile material (20%)

ii – nuclear fusion

fusion power is an experimental technology with [hydrogen](#) as fuel, and it is not currently established as power generation system, although it is a [highly advanced military weapon](#) at the present time, where [hydrogen bomb](#) have been tested and approved as the most [powerful destructive weapon](#) actually produced by mankind.

iii – radioactive decay

Radioactive decay is the process by which an [atomic nucleus](#) of an unstable atom loses energy by emitting ionizing particles ([ionizing radiation](#)). The emission is spontaneous, in that the atom decays without any interaction with another particle from outside the atom (i.e., without a [nuclear reaction](#)).

Radioactive decay is a random process at the level of single atoms, and it is impossible to predict when a given atom will decay. However, given a large number of identical atoms (nuclides), the decay rate for the collection is predictable, via the [Law of Large Numbers](#).

2 – moderator material

1. Graphite moderated reactor
2. Water moderated reactor (heavy & light water).
3. Light element moderated reactor (molten salt & liquid metal cooled reactors)
4. Organically moderated reactor

3 - coolant

1 – water cooled reactor

i- pressurized water reactor (PWR)

ii- boiling water reactor (BWR)

iii- pool type reactor

2 – liquid metal cooled reactor

i- sodium-cooled

ii- lead-cooled

3 – gas cooled reactor

4 – molten salt reactor

4 – reactor generation (age)

1. Generation - I –
2. Generation - II – (most current NPP)
3. Generation - III – (improved of existing design)
4. Generation - IV – (technology still under development)

5 – phase of fuel

1. Solid fueled
2. Fluid fueled
3. Gas fuelled

6 – application & usage

- 1 – electricity production (NPP)
- 2 – nuclear propulsion
 - I – nuclear marine propulsion.
 - ii – rocket propulsion
- 3 – heat utilization
 - I – domestic & industrial heating
 - ii – desalination (desalting)
 - iii – hydrogen production
- 4 – reactor production
 - I – breeder reactor
 - ii – creating radioactive isotopes
 - iii – nuclear weapons
- 5 – providing source of neutron radiation
- 6 – research reactor